High-Strength Aluminum Alloys

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Outline

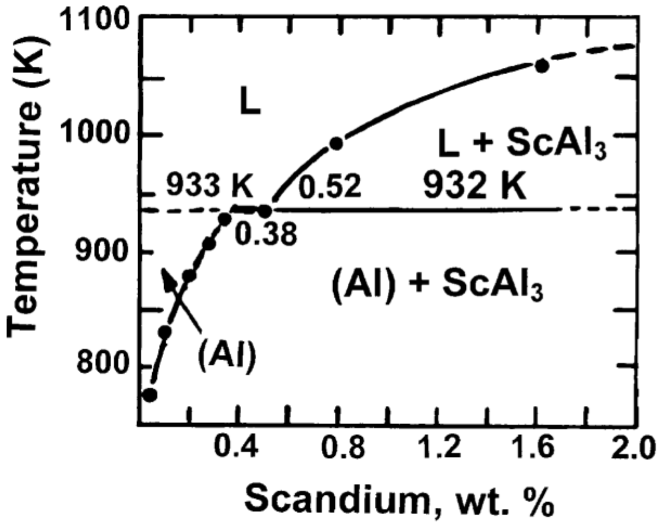
1. Introduction.
2. ”Sc effect” of improving mechanical properties in aluminum alloys.
3. High-strength Al - Zn - Mg - Cu alloys, additionally alloyed by Sc.
4. Aluminum alloys hardened by quasicrystalline particles for elevated temperature.
5. High-strength cast eutectic aluminum alloys.
6. Cast eutectic aluminum alloys containing $L1_2$ phase.

Mechanical properties of structureal light alloys

[*M.Ashby & D.Jones, 1992*]

Alloy	Density ρ [Mgm^{-3}]	Young's modulus E [GPa]	Yield strength σ_y [MPa]	$\frac{E}{\rho}$	$\frac{E^{1/2}}{\rho}$	$\frac{E^{1/3}}{\rho}$	$\frac{\sigma}{\rho}$	$\frac{\sigma_y^{2/3}}{\rho}$	$\frac{\sigma_y^{1/2}}{\rho}$	Creep temperature [^oC]
Al alloys	2.7	71	25 – 700	26	3.1	1.5	9 – 260	3.2 – 29	1.9 – 9.8	150 – 250
Mg alloys	1.7	45	70 – 270	25	4.0	2.1	41 – 160	10 – 24.5	4.9 – 9.7	150 – 250
Ti alloys	4.5	120	170 – 1280	27	2.4	1.1	38 – 280	6.8 – 26.1	2.9 – 7.8	400 – 600
Steels	7.9	210	220 – 1600	27	1.8	0.75	28 – 200	4.6 – 17.2	1.9 – 5.1	400 – 600

«Sc effect» of strength increasing in Al alloys



Positive effect of Sc on the mechanical properties of Al is stipulated by the disperse hardening, generated by the *Al_3Sc* intermetallic compounds.

Sc is also characterized by the *modifying effect*, decreasing the *grain size* in as-cast state and the sensitivity to the *recrystallization.*

Content of Sc in the α solid solution is 0.5; 1.2 and 3.0 mass.% at cooling rates v = 10^2; 10^3 and 10^5 K/s.

The quenching temperature is 620 – 640 ^{o}C and the decomposition of solid solution after quenching occurs at 250 – 400 ^{o}C.

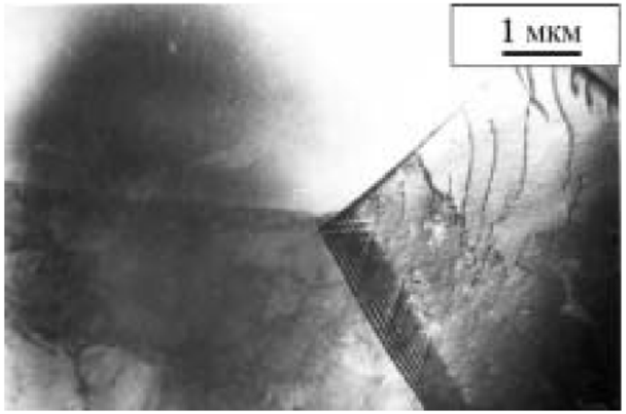
Al_3Sc phase is characterized by high structural and dimensional match with the aluminum matrix.

$$\frac{\Delta\sigma_s}{\Delta C_{at}} = 1000\ \frac{\mathrm{MPa}}{\mathrm{at}\%}$$

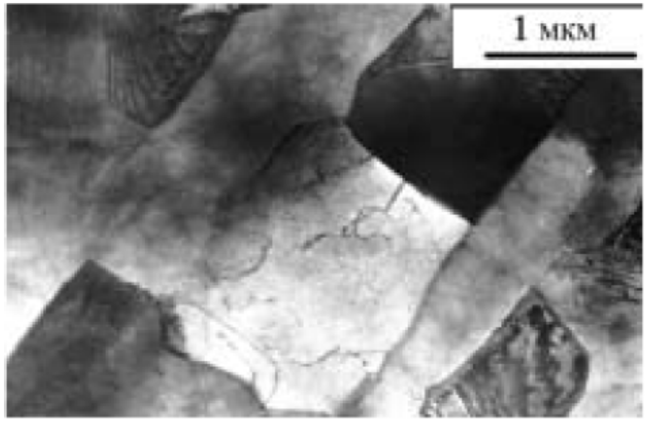
$$\delta = \frac{\Delta a}{a} = 1.2\ \%$$

that is much greater than for other elements in Al.

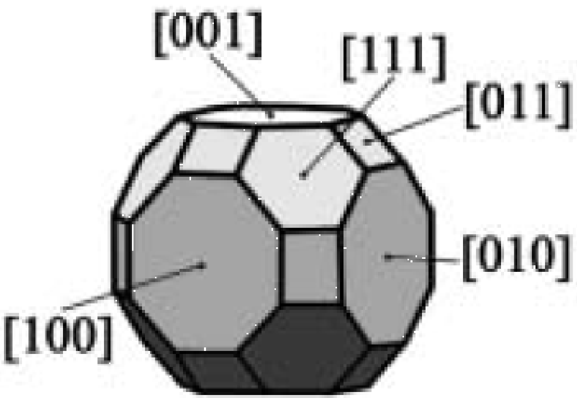
Dislocation cells in Al alloys



Al – 4.9%Mg



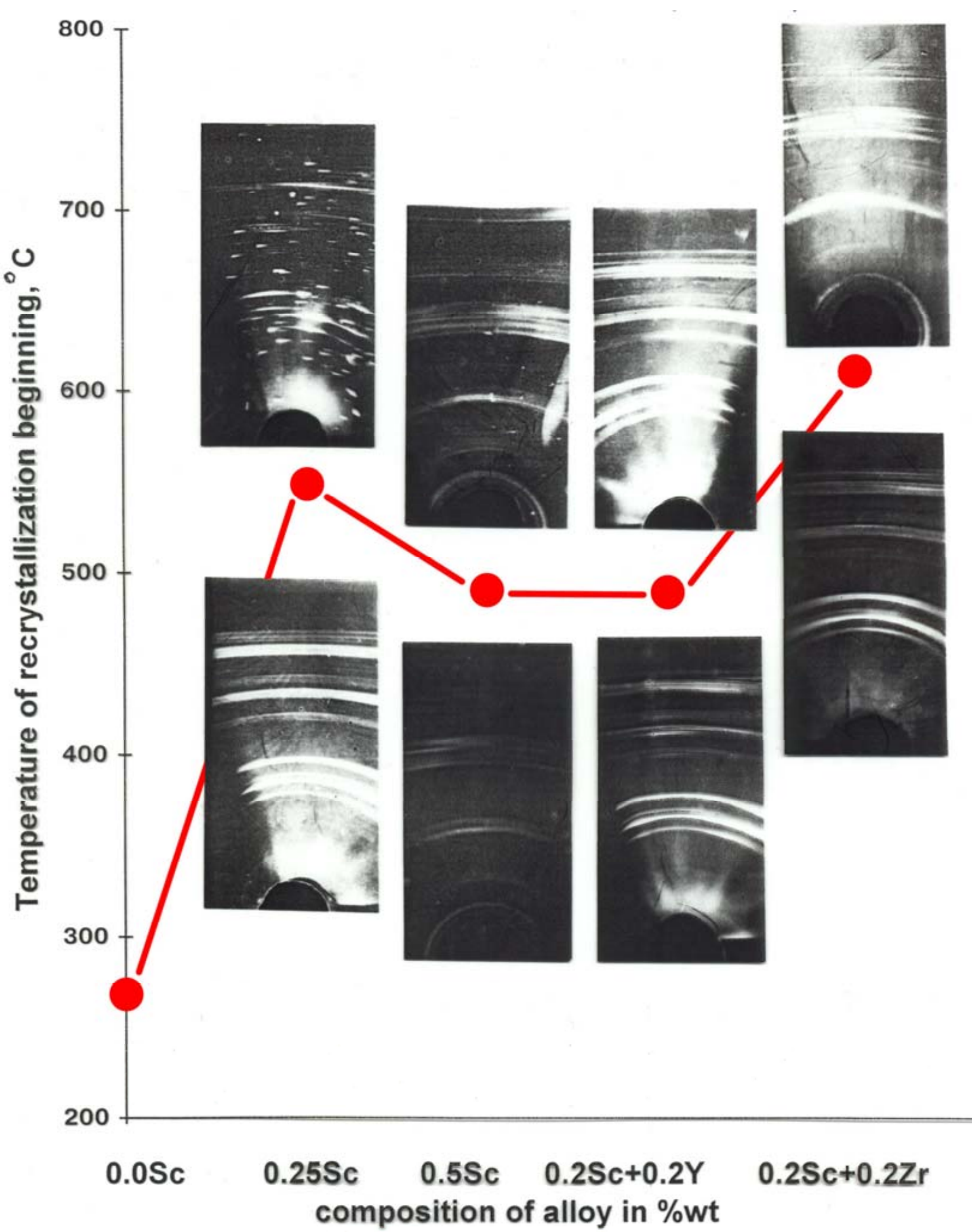
Al – 5.2%Mg – 0.3%Sc



The shape of Al_3Sc precipitate [*E.A.Marquis & D.N.Seidman, 2001*]

Element	Sc	Mg	Si	Cu	Zn
U, eV	0.35	0.29	0.26	0.20	0.18

The binding energy between vacancy and soluble elements in α-Al

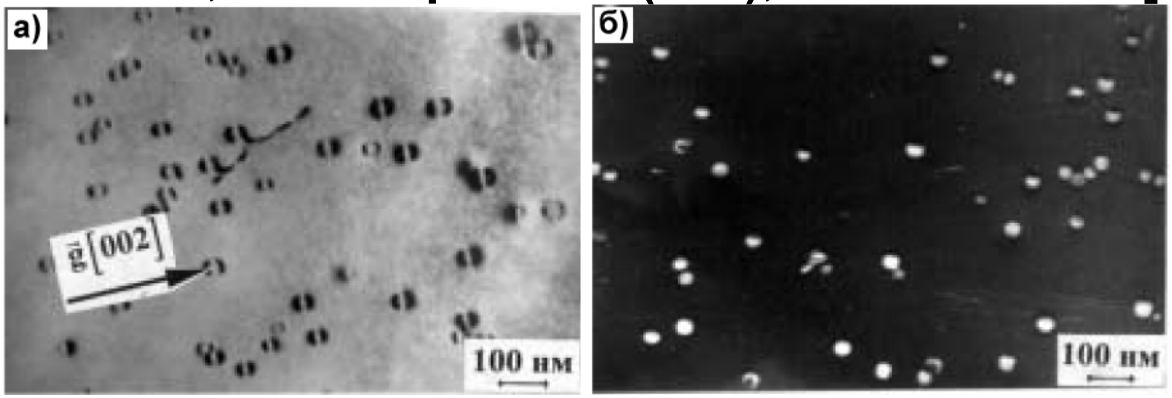


The increase of the temperature of recrystallization beginning in Al-Sc alloys with the additions of Zr and Y (ε = 80 %)

$Al_3(Sc_{1-x}Zr_x)$ particles in the cast alloy Al-6.8Zn-1.3Mg-0.12Zr-0.05Sc (wt.%) homogenization 470°C, 3 h (TEM):

a) bright field, the foil plane is (110), the reflection [002];

b) dark field, the foil plane is (110), the reflection [002]



The temperature of the recrystallization T_r for Al alloys with Sc

Composition of alloys (wt.%)	T_r, °C
Al	100-200
Al-0.26Sc	540
Al-0.2Sc-0.18Zr	610
Al-7Zn-2Mg-0.14Zr-0.2Sc	Recrystallization is absent up to the melting point
Al-6Mg-0.14Zr-0.2Sc	Recrystallization is absent up to the melting point

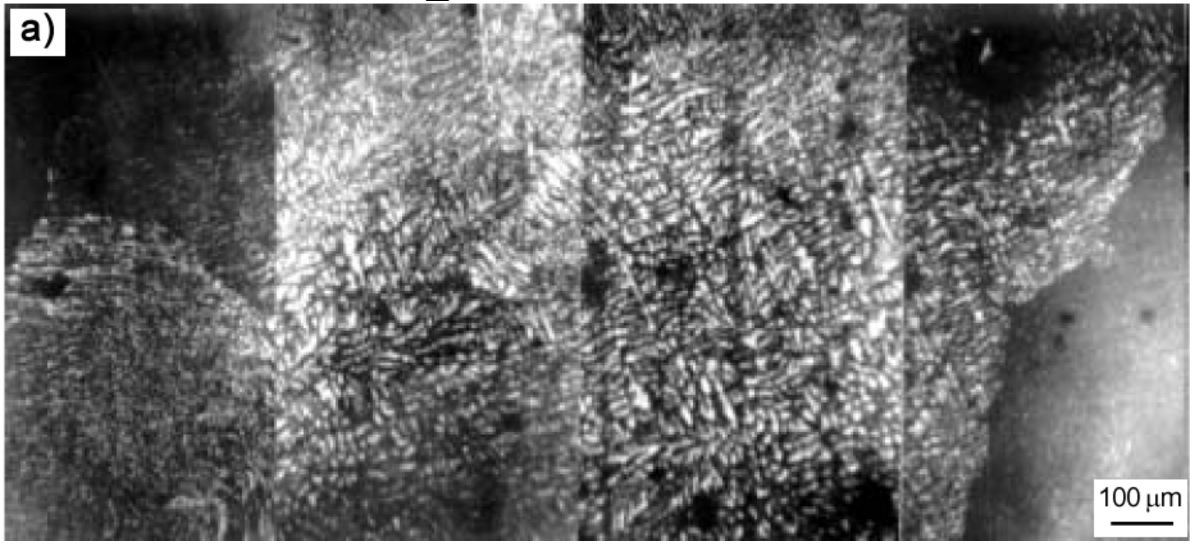
"Sc effect" on the workability of cast alloys in rolling from 60 mm to 1 – 3 mm in thickness (without extrusion)

Alloy	Production output [%]		
	0 % Sc	0.2 % Sc	0.5 % Sc
6061: Al-1.0Mg-0.6Si-0.2Cr-0.28Cu	100	100	100
2195: Al-4.1Cu-1.05Li-0.4Mg-0.14Zr	50	75	90
7075: Al-5.6Zn-2.5Mg-1.6Cu-0.23Cr	20	30	100
2618: Al-2.3Cu-1.5Mg-1.1Fe-1.1Ni-0.15Si	50	75	95
2024: Al-4.3Cu-1.5Mg-0.6Mn	15	50	100

Influence of scandium on the modification of cast alloy structure

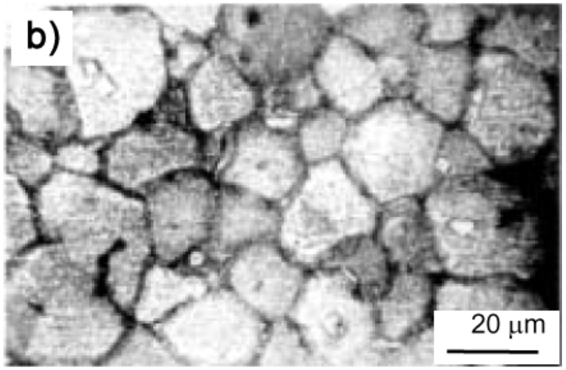
Alloy	Grain size [μm]		
	0 % Sc	0.2 % Sc	0.5 % Sc
2195: Al-4.1Cu-1.05Li-0.4Mn-0.14Zr	72	55	30
2024: Al-4.3Cu-1.5Mg-0.6Mn	60	45	22
7075: Al-5.6Zn-2.5Mg-1.6Cu-0.23Cr	60	53	15
2618: Al-2.3Cu-1.5Mg-1.1Fe-1.1Ni-0.15Si	36	16	14

Microstructure of ingots of Al – 9.5Zn – 3Mg – 1.2Cu – (Zr, Sc) alloys, longitudinal section



a – alloy 1 (baseline = Al–9.5Zn–3Mg–1.2Cu)

b – alloy 3 (baseline + Zr + Sc)



Classification of the alloying elements in relation to the «Sc effect» in Al alloys

The character of the phase equilibrium diagram Al-Me and Sc-Me (Me is the alloying element) has been selected as a basis for the present classification.

1. Elements which increase or don't decrease significantly the solidus temperature of aluminum T_s and don't form with Sc strong intermetallics distributed in aluminum solid solution (Ti, Zr, Hf, V, Nb, Ta, Mn, Cr, Mo, W, Re, i.e. mainly transition metals);

2. Elements which lower T_s, but have high solubility in Al at the temperature of ageing by Sc (about 300 °C). They are in the first line Zn, Mg, Li;

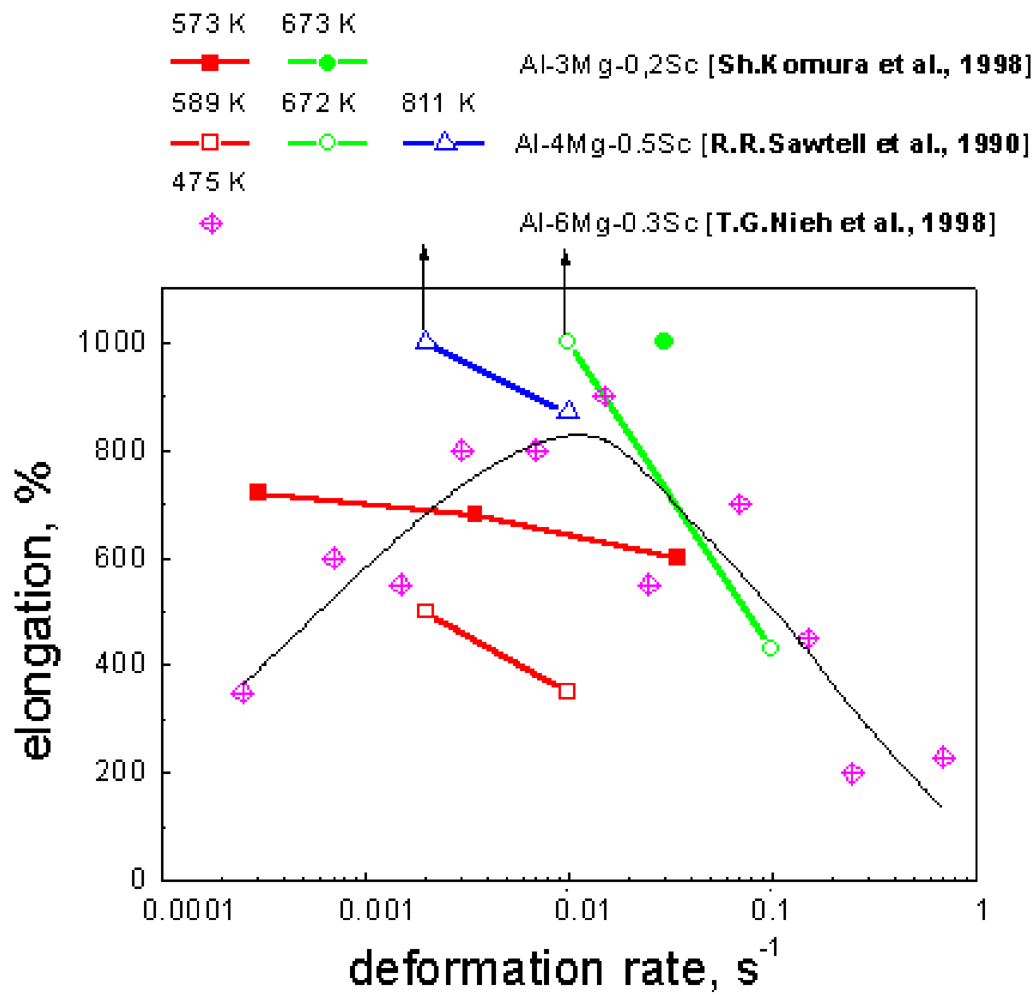
3. Elements which lower T_s and have low solubility at the temperature of ageing by Sc (Cu and Si);

4. Elements which form strong compounds with Sc and exclude Sc from hardening process (Fe, Co, Ni, and Cu and Si at high concentrations as well);

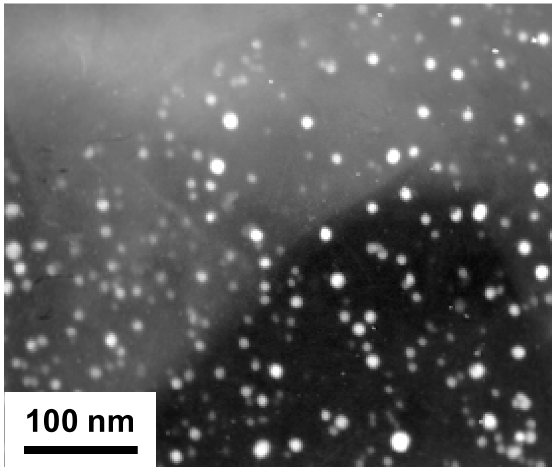
5. Elements which partially substitute Sc in Al_3Sc and lower the consumption of Sc with the preservation of hardening effect (Zr, Y and rare-earth elements).

Some elements (Zr, Cu, Si et al.) may have the properties of several groups.

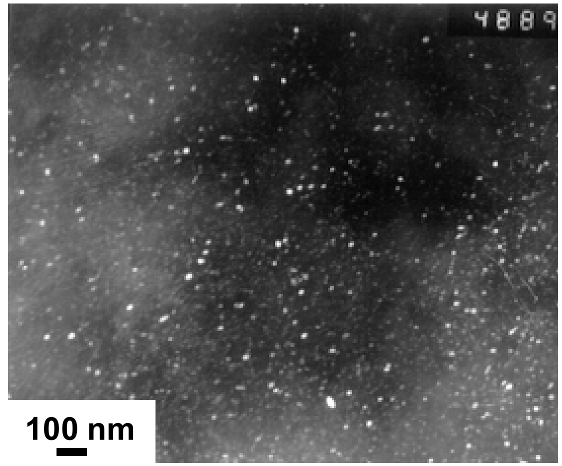
The influence of the deformation rate on plasticity to fracture for Al-Mg alloys, containing Sc



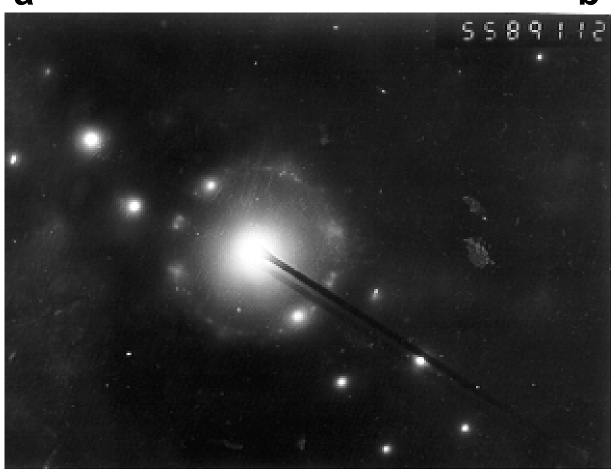
Secondary particles in rods of the alloy Al-Zn-Mg-Cu-Sc-Zr after T6 treatment



a



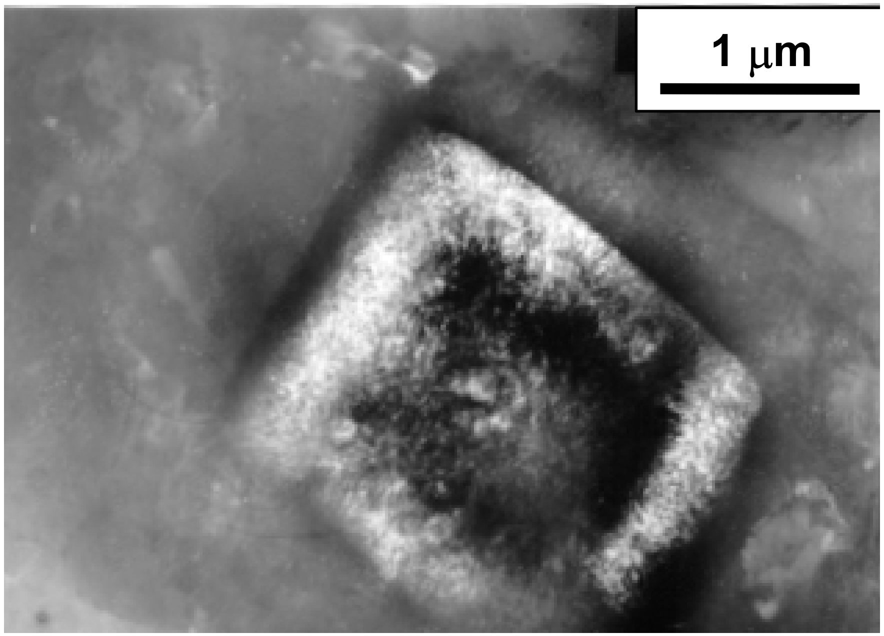
b



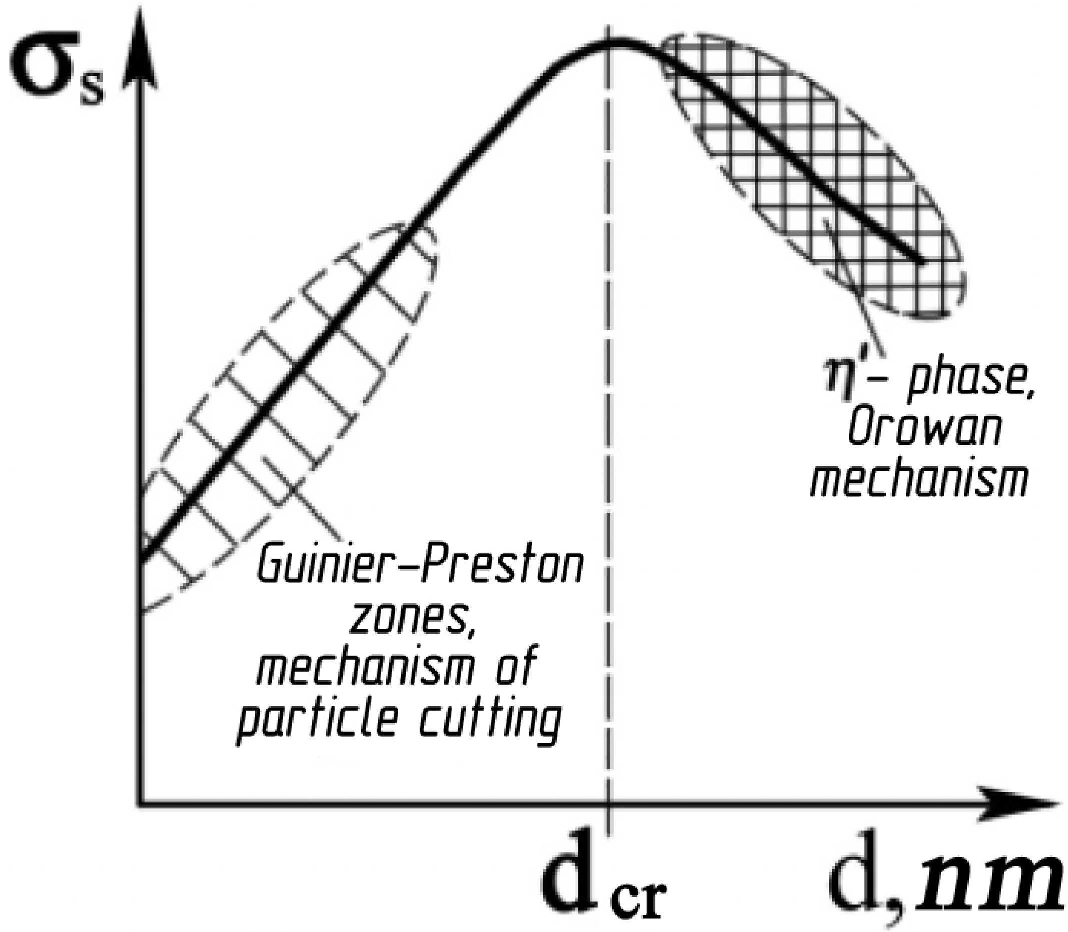
c

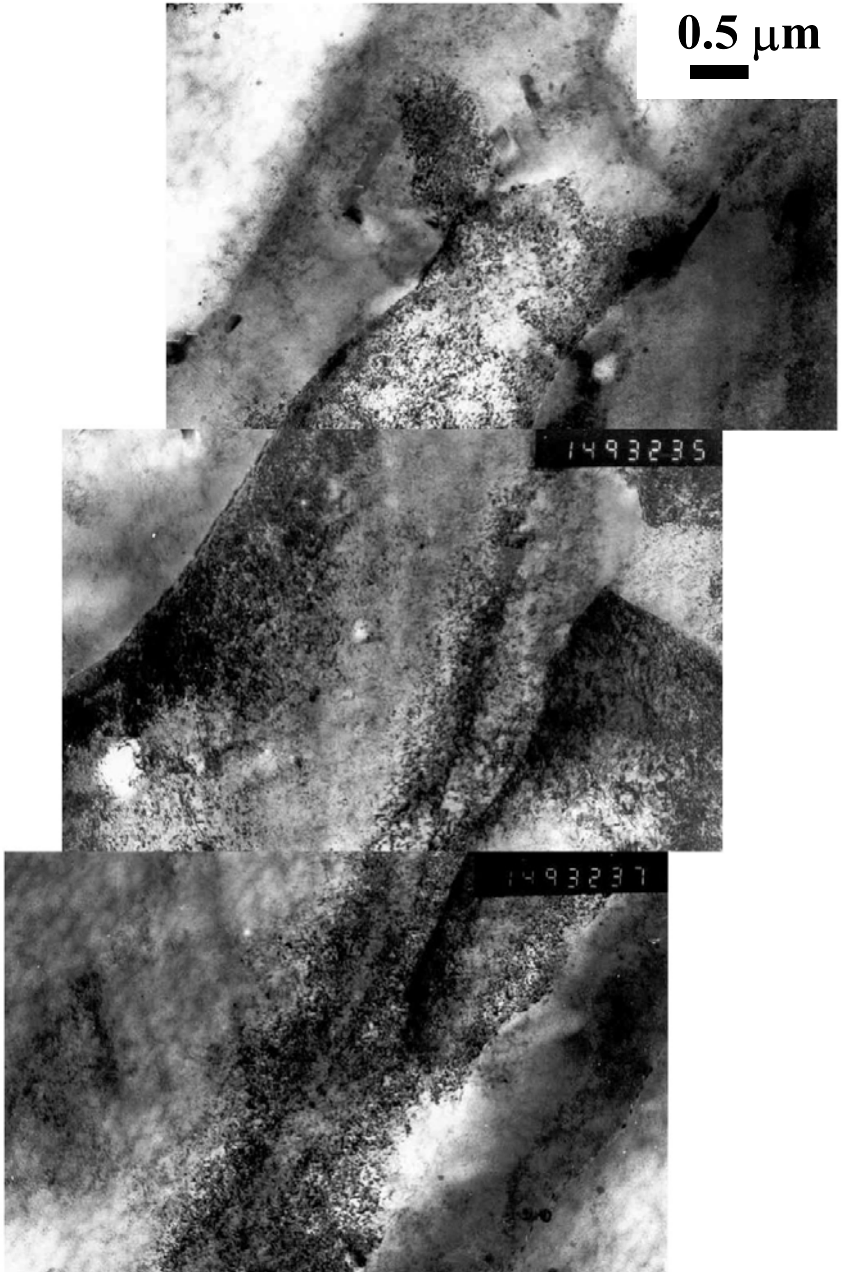
(a) dark field image of $Al_3Sc_{1-x}Zr_x$ particles after quenching from 460 ^oC and aging at 120 ^oC 24 h [001]; (b) dark field image of $MgZn_2$ particles in the same alloy obtained in reflections in the ring (c)

A primary particle $Al_3Sc_{1-x}Zr_x$ in the extruded rod from cast alloy, dark field image in (001) reflection of Al_3Sc



Scheme of the dependence of the yield stress σ_s on the average size of second phase particles in Al - Zn - Mg alloys [*Kovác et al., 1980*]



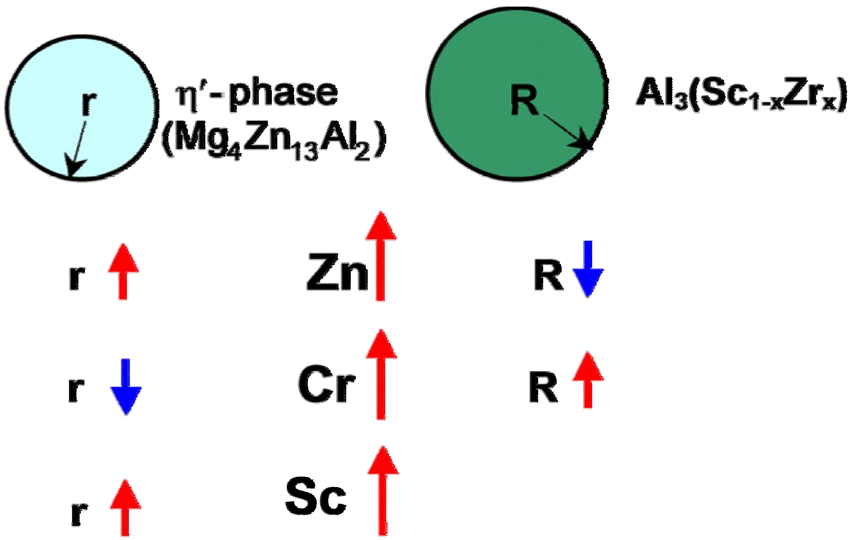


The band of localized deformation in the working part of specimen after the tension test of alloy Al – Zn – Mg – Cu system

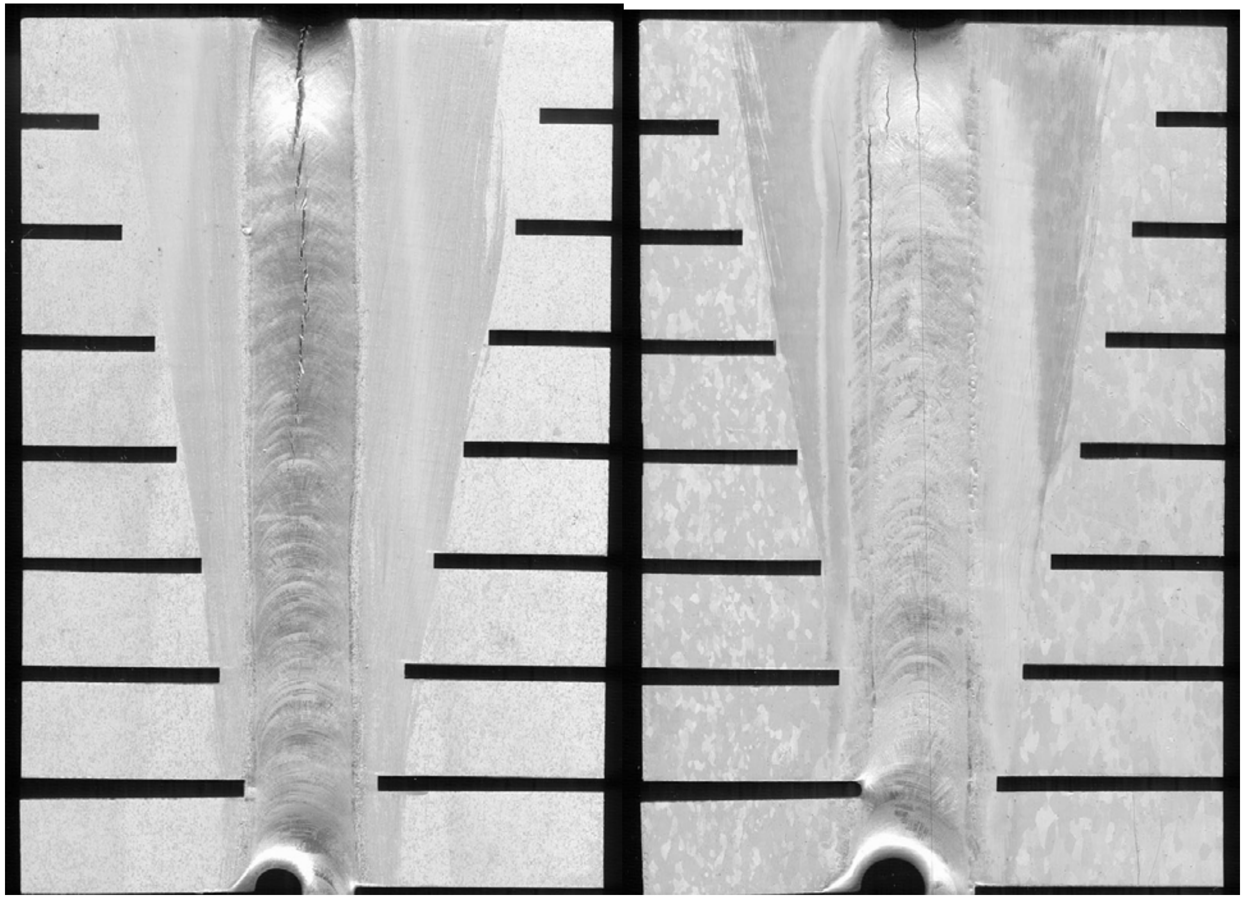
in T6 condition

Structural parameters of extruded rods (after T6 treatment) of Al - Zn - Mg - Cu alloys additionally alloyed by Zr, Sc and Cr

Alloy #	Content of Zn, %wt.	Transverse size of dislocation cell, μm	Longitudinal size of η′-phase particles, μm	Size of $Al_3(Sc_{1-x}Zr_x)$ particles, μm
Л10	10	1.8	8.2 (Zr)	-
Л13	10	1.3	9.6 (Zr, Sc)	5.7
Л11	10	1.0	2.9 (Zr, Cr)	-
Л12	10	1.3	3.5 (Zr, Cr, Sc)	11.8
Л14	10	1.7	6.2 (Zr, Mn)	-
Л15	10	1.6	12.5 (Zr, Mn, Sc)	6.6
Л16	12	1.5	6.6 (Zr, Mn, Sc)	8.5
UM27	5	1.9	2.2 (Zr)	13.5 (Al_3Zr)
UM28	5	1.0	(Zr, Cr, Sc)	12.0
UM29	5	1.5	3.17 (Zr, Sc)	11.2
UM30	5	2.0		



Houldcroft tests for hot cracking susceptibility



a b

Types of weld cracking in arc welding of Al - Zn - Mg - Cu alloys without Sc
a – in weld center; b – in different weld zones

Houldcroft tests for hot cracking susceptibility

a

b

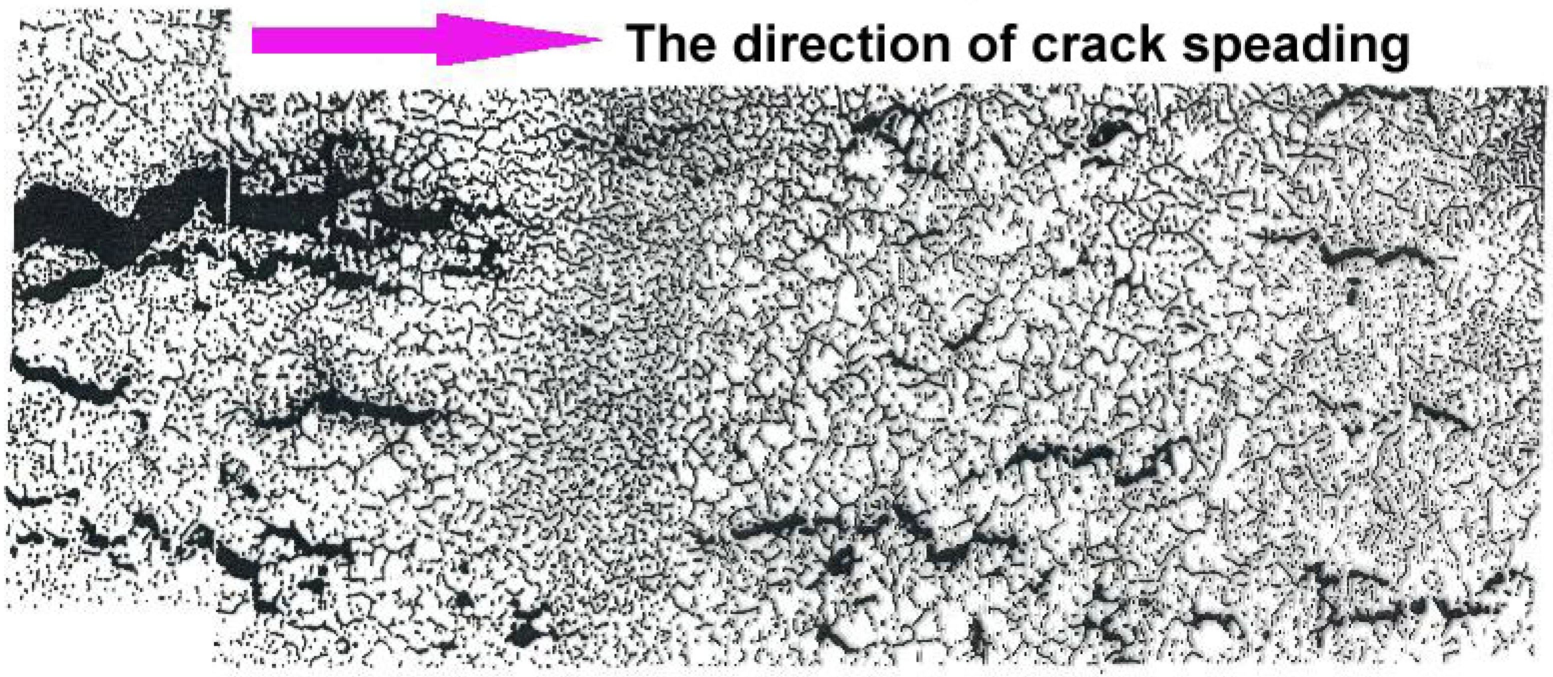
Appearance of the technological samples in arc welding of test alloys without a filler:

a – alloy L2 (Al-8.0%Zn-2.3%Mg-2.0%Cu-0.1%Mn-0.1%Cr-0.2%Zr-0.4%Sc);

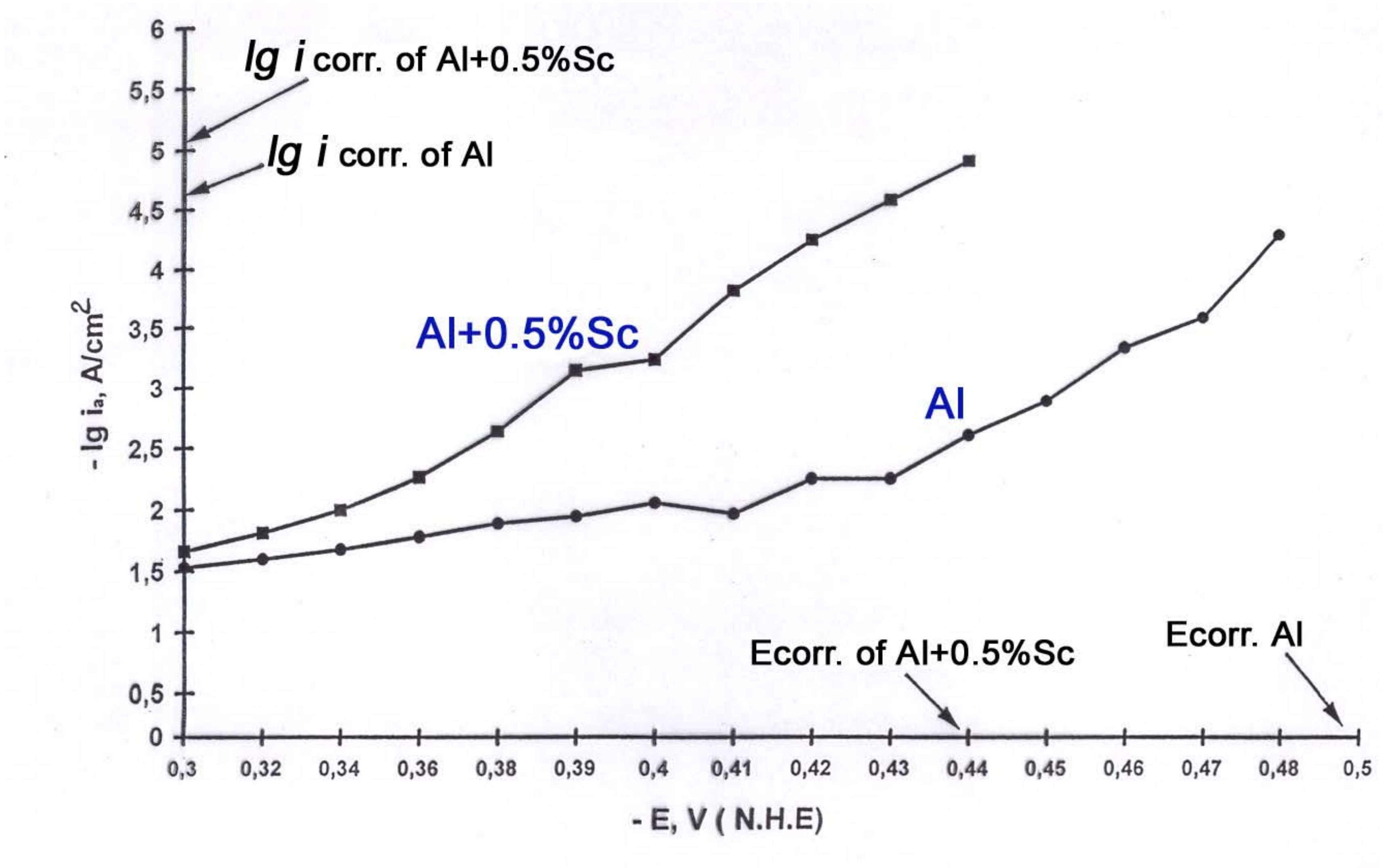
b – alloy L3 (10.0%Zn-3.5%Mg-3.0%Cu-0.2%Zr-0.3%Sc).

No cracks found

An example of stopping a hot crack in the area of the weld with subdendrite structure stipulated by the presence of Sc > 0.3 %; x100



Effect of Sc on corrosion and ectrochemical properties of Al in water solution 3 % NaCl, 25 ^{o}C



The influence of alloying elements on the mechanical properties of Al - 9Zn - 3Mg - 2.3Cu alloy in T6 condition

<table>
<tr><th colspan="3" rowspan="2">Alloy</th><th rowspan="2">Elements</th><th colspan="3">Mechanical property of rods ∅ 6 mm in T6 conditional</th></tr>
<tr><th>YS, MPa</th><th>UTS, MPa</th><th>El,%</th></tr>
<tr><td rowspan="4">UM10= UM 8 + Sc</td><td rowspan="3">UM 8 = UM 7.2 + Zr</td><td rowspan="2">UM 7.2 = UM 22 + Mn</td><td>UM 22 Al-9Zn-3Mg-2.3Cu</td><td>530</td><td>619</td><td>20.4</td></tr>
<tr><td>+Mn</td><td>548</td><td>636</td><td>17</td></tr>
<tr><td colspan="2">+ Zr</td><td>545</td><td>621</td><td>13.8</td></tr>
<tr><td colspan="3">+ Sc</td><td>696</td><td>789</td><td>12.3</td></tr>
<tr><td colspan="3" rowspan="8">UM 10 + TM and RE metals</td><td>+V</td><td>717</td><td>767</td><td>7.3</td></tr>
<tr><td>+Ni</td><td>735</td><td>807</td><td>10.2</td></tr>
<tr><td>+Nb</td><td>722</td><td>824</td><td>11.4</td></tr>
<tr><td>+Ce</td><td>744</td><td>809</td><td>10.0</td></tr>
<tr><td>+Cr</td><td>725</td><td>804</td><td>10.2</td></tr>
<tr><td>+Hf</td><td>700</td><td>810</td><td>14.1</td></tr>
<tr><td>+Ti</td><td>718</td><td>779</td><td>10.3</td></tr>
<tr><td>+Fe</td><td>741</td><td>802</td><td>9.3</td></tr>
<tr><td colspan="3">UM 8 + Ti</td><td>+Ti</td><td>654</td><td>707</td><td>7.2</td></tr>
</table>

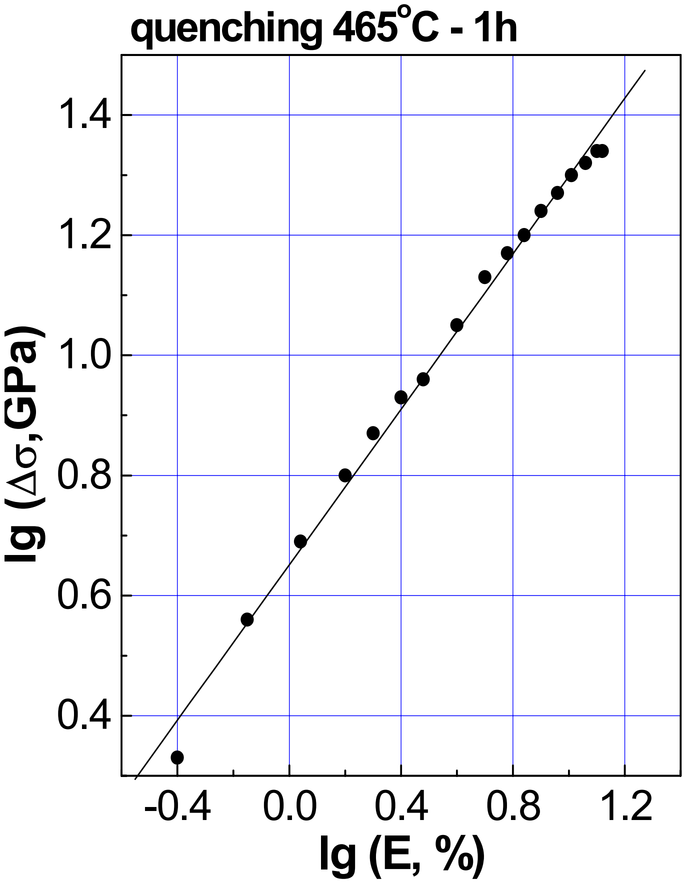
Mechanical properties of Al-Sc alloys

Designation of alloy	*Standard alloys*			New alloys, alloyed by Sc in additions					
				Cast technology			*PM technology*		
	Yield stress [MPa]	UTS [MPa]	δ [%]	Yield stress [MPa]	UTS [MPa]	δ [%]	Yield stress [MPa]	UTS [MPa]	δ [%]
Al – Zn – Mg									
1915 (rod)	350	400	10	520	570	13	700	770	9
1915 (sheet)	280	360	11						
7046 (rod)	427	469	13						
7046 (sheet)	379	414	13						
Al – Zn – Mg – Cu									
B95 (7075) (rod)	550	580	8	740	810	10	750	800	8
B95 (7075) (sheet)	480	530	11						
B96Ц1 (8055)	620	650	6						
Al – Mg									
AMr 5M (5056)	180	300	20	480	520	10	510	570	8
AMr 5H	320	420	10						
AMr 6HH	340	420	8						
Al – Mg – Li									
1420	290	440	11	540	590	6			

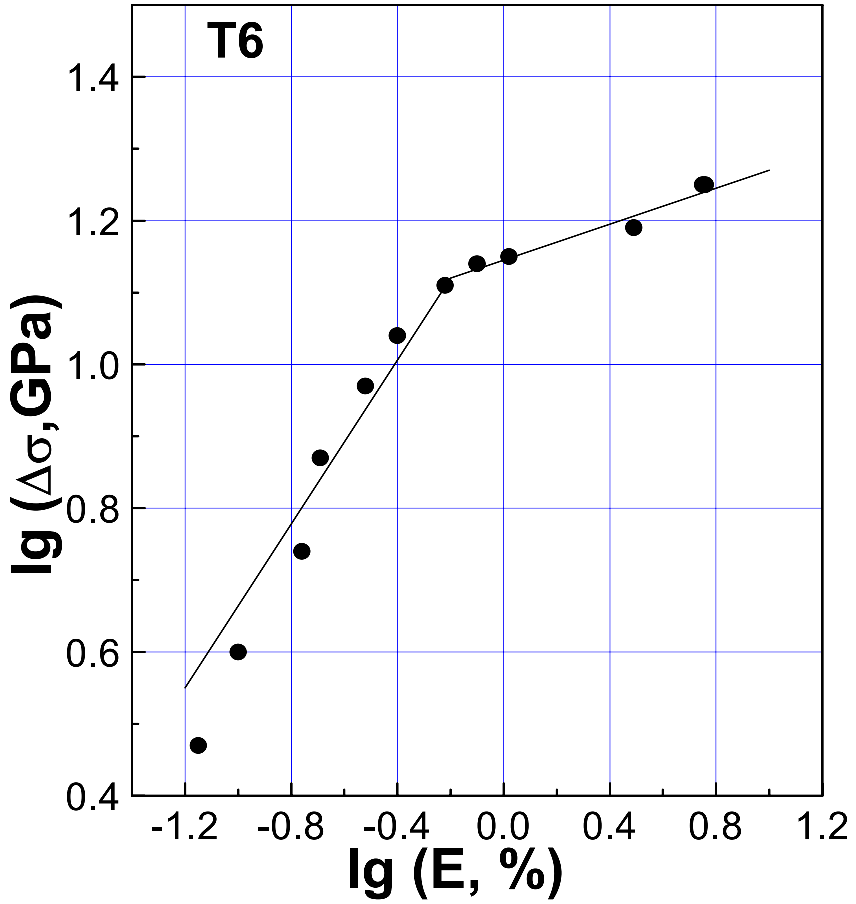
Hardening $\Delta\sigma$, versus deformation E of rod sample

alloy 4 Al–10.3Zn–2.85Mg–1.19Cu–0.15Zr

a – quenching from 465 °C after 1 h holding; b – after T6 treatment



a



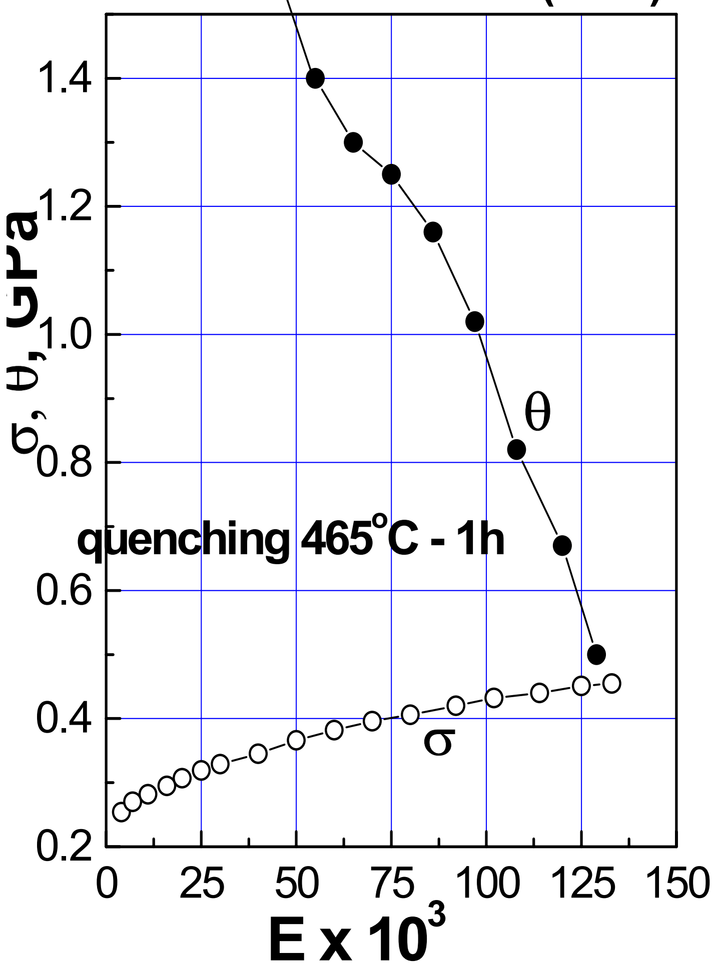
b

True stress σ and strain hardening coefficient θ for rod samples

alloy 4 Al–10.3Zn–2.85Mg–1.19Cu–0.15Zr

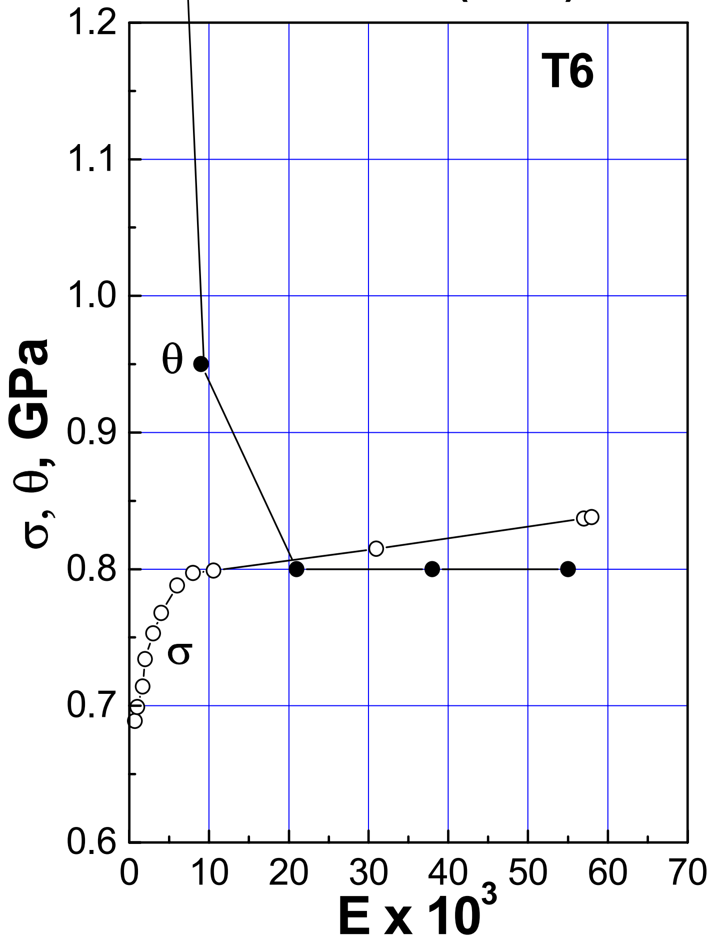
c – quenching from 465 °C after 1 h holding; d – after T6 treatment.

θ = 5.33 GPa at E = 0.005(0.5%)



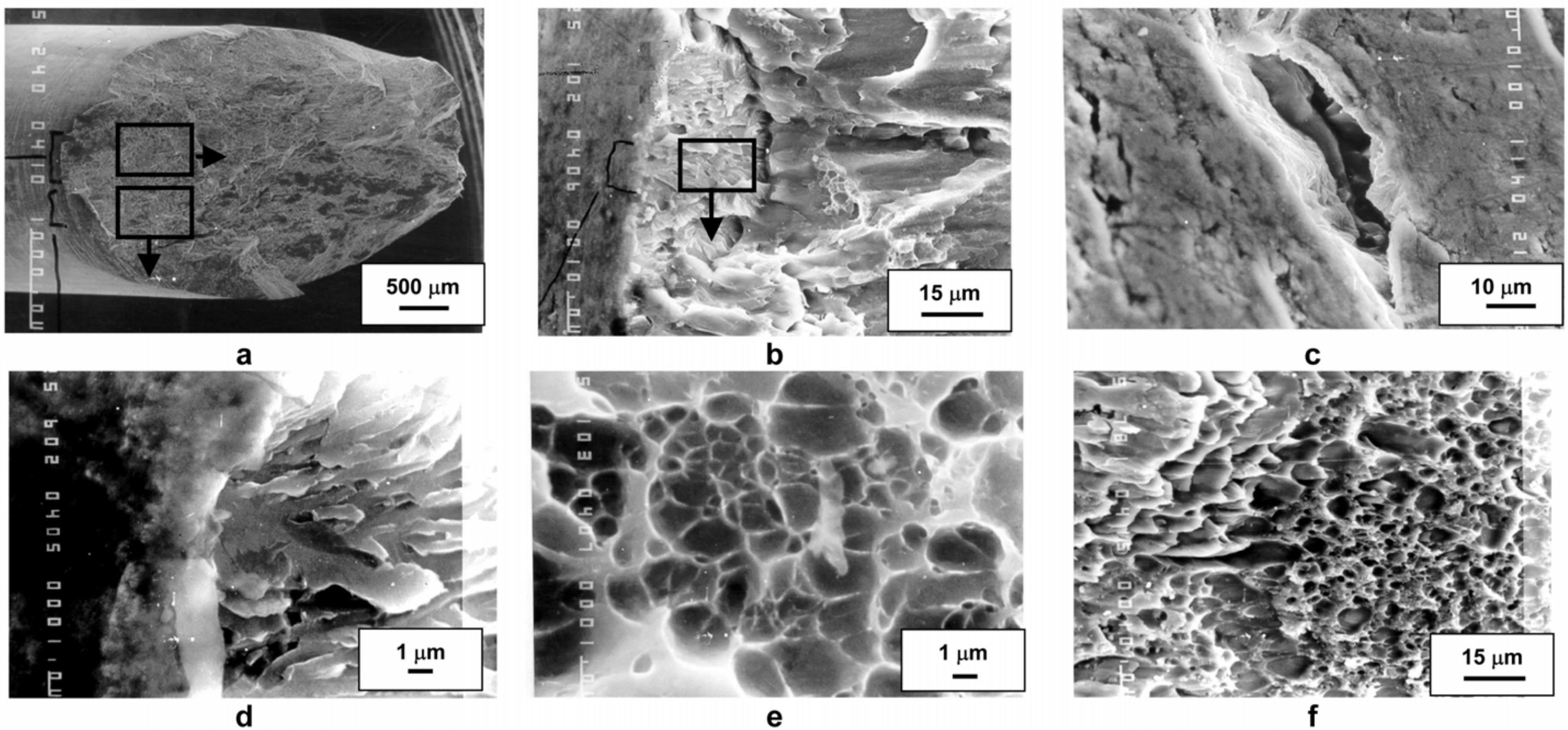
c

θ = 34.6 GPa at E = 0.001(0.1%)

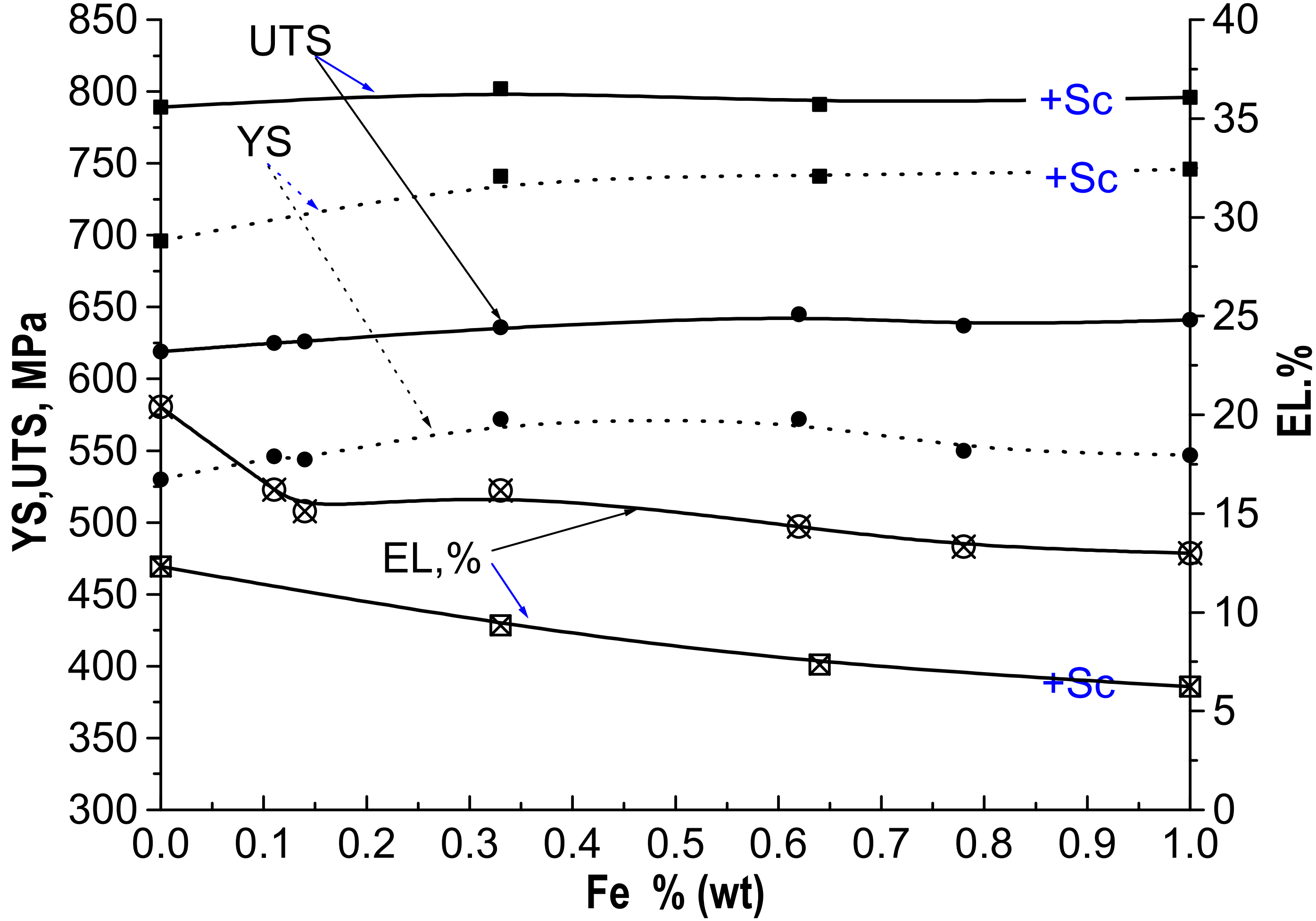


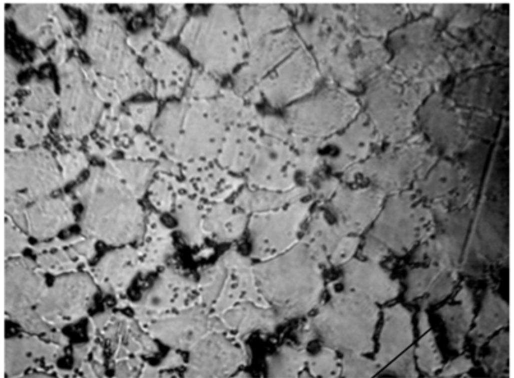
d

Fracture surface of the rod from alloy 4
(Al – 10.3Zn – 2.85Mg – 1.19Cu – 0.15Zr)
after T6 treatment (aging at 120 ^{0}C, 24 h)

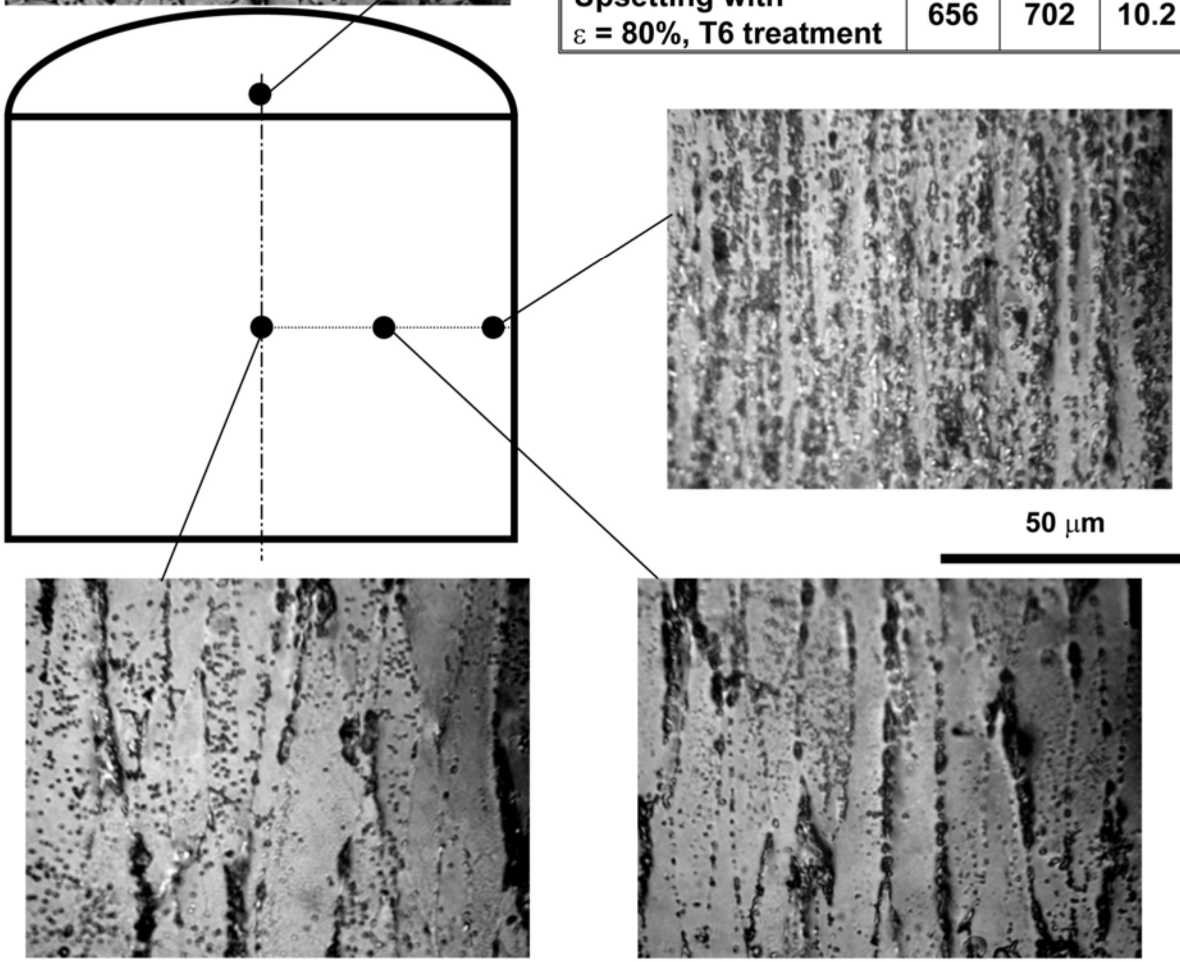


The influence of iron concentration on the mechanical properties of rods ∅ 6 mm (μ =17.7) Al - Zn - Mg - Cu alloys in T6 conditions. Alloys obtained by casting. Alloy 1: Al - 9Zn - 3Mg - 2.3Cu + (x)Fe; alloy 2: Al - 9Zn - 3Mg - 2.3Cu - 0.3Mn - 0.15Zr - 0.3Sc + (x)Fe



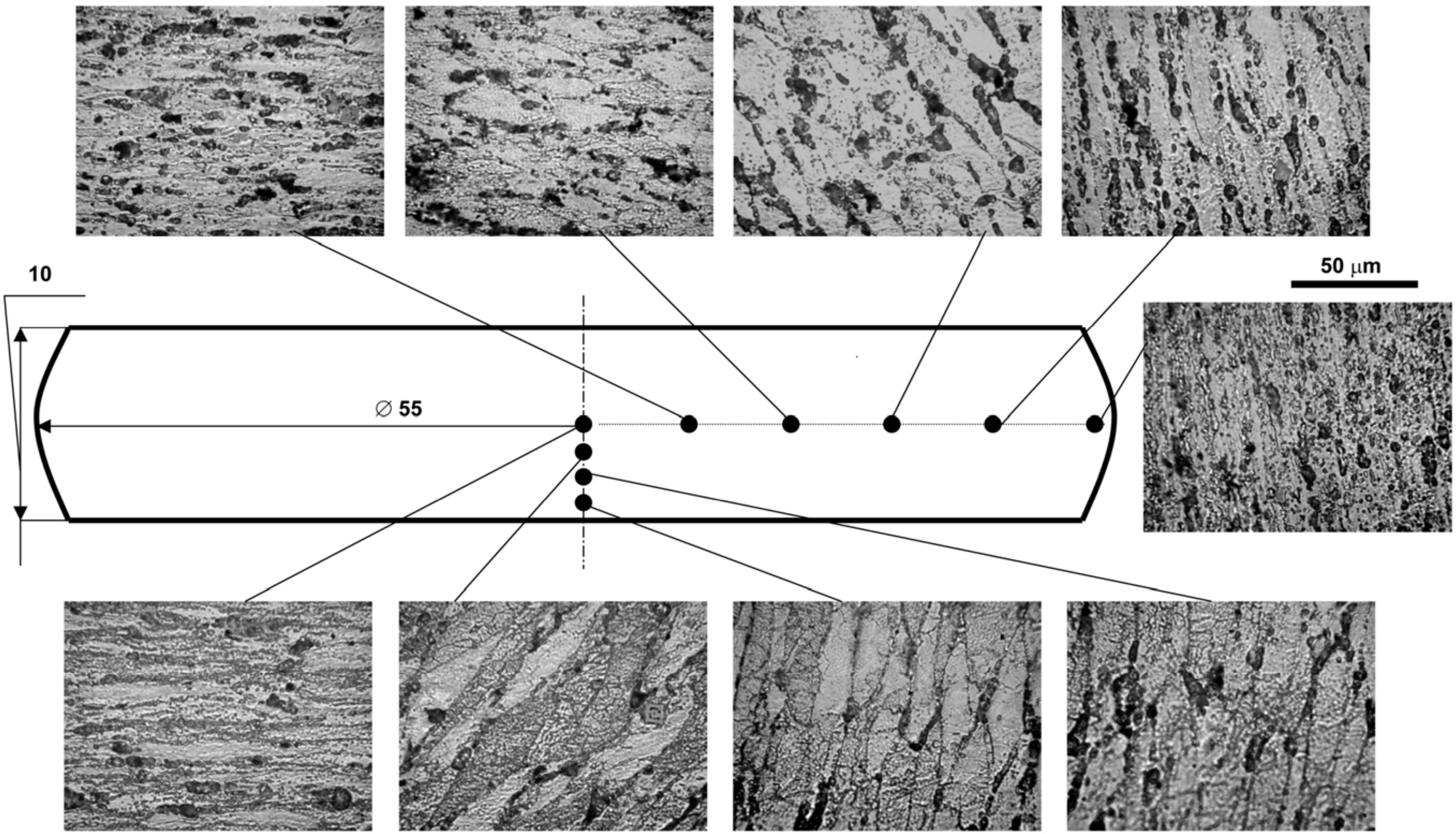


Mechanical properties	YS, MPa	UTS, MPa	EL, %
Extrusion with λ=18, T6 treatment	675	710	9
Upsetting with ε = 80%, T6 treatment	500	578	19
Extrusion with λ=4, T6 treatment	683	725	12
Upsetting with ε = 80%, T6 treatment	656	702	10.2

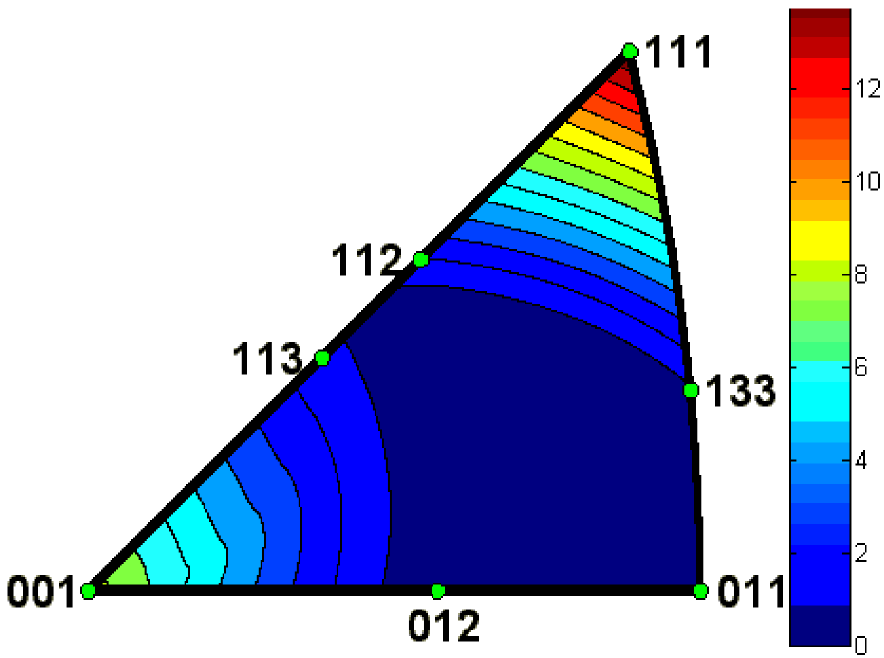


Structural texture of the extruded rod of 25 mm in diameter of the Al-9Zn-3Mg-2.3Cu-0.3Mn-0.3Sc alloy

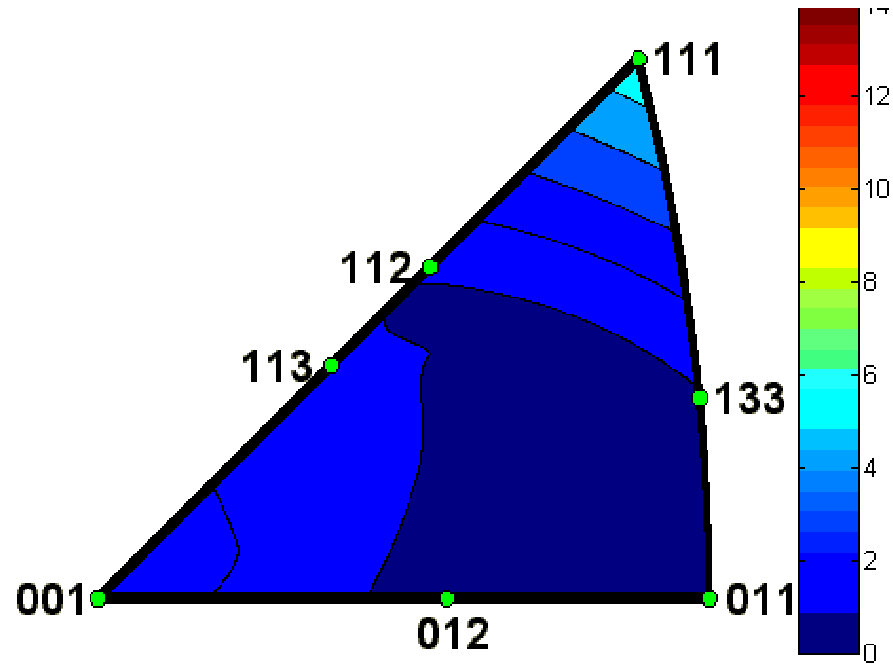
Structural texture in section along the axis of the upset billet (obtained from the extruded rod) of Al-9Zn-3Mg-2.3Cu-0.3Mn-0.3Sc alloy (ε = 80%)



Inverse pole figures of the extruded rod and of the upset billet (obtained from this extruded rod) of the Al-9Zn-3Mg-2.3Cu-0.3Mn-0.3Sc alloy

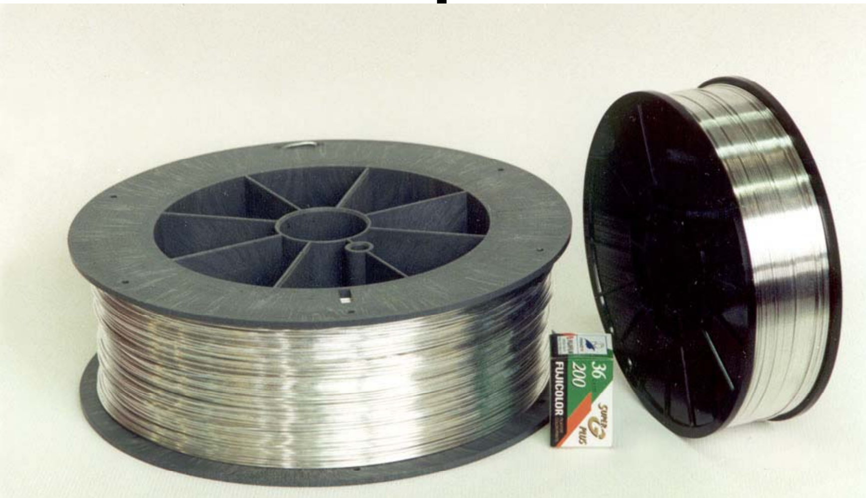


extruded rod



upset billet

Samples of articles from Al-Sc alloys

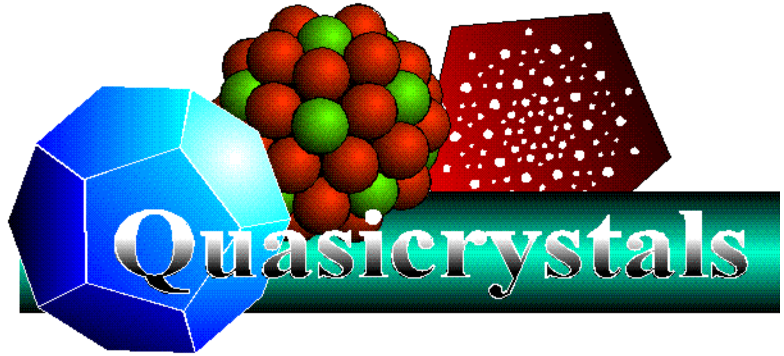


Al-Sc wire for welding

Baseball club from Al-Sc alloys

Tubes from Al-Sc alloys

Balloon from Al-Sc alloys



Quasicrystals are new perspective materials, in which

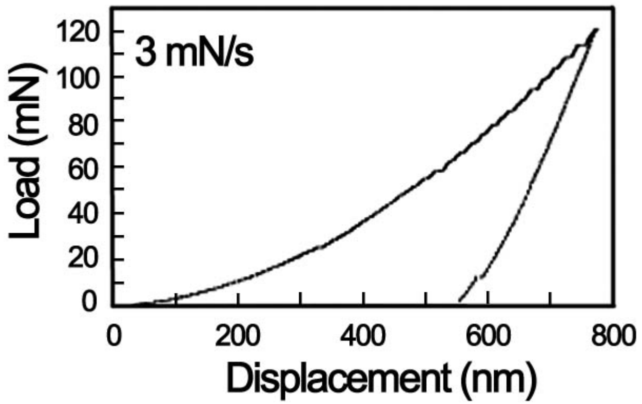
- ♦ the translational long-range is absent;
- ♦ there is a rotational symmetry with 5-, 8-, 10- or 12-fold axes (that is forbidden in crystalline materials);
- ♦ high hardness (up to 10 GPa), brittleness while standard testing and plasticity at local loading are observed.

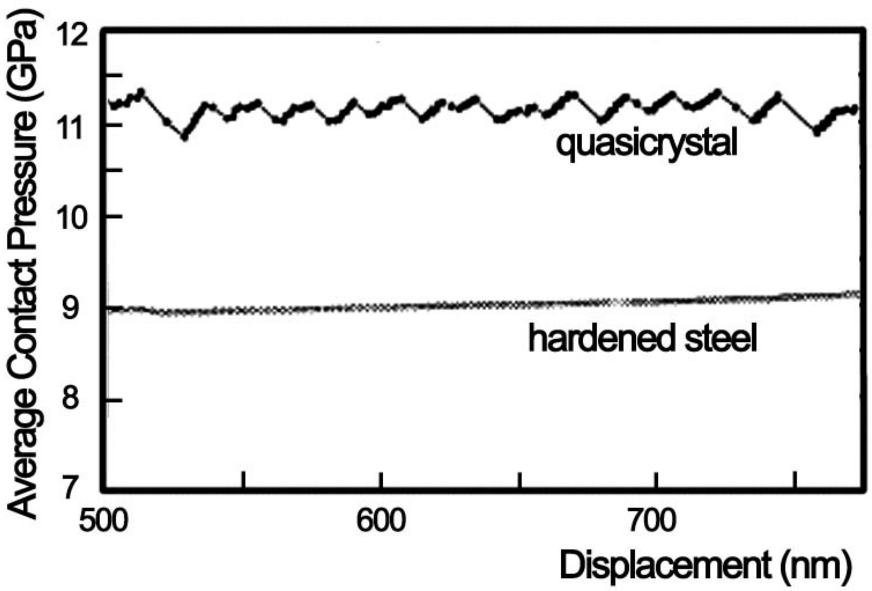
It was shown in previous works of authors that the plasticity at local loading is a result of the phase transition to a crystalline structure. It is proved by:

- serrated yielding during nano-hardness measurement;
- extrusions of ductile phase around the indent;
- special shape of the indents.

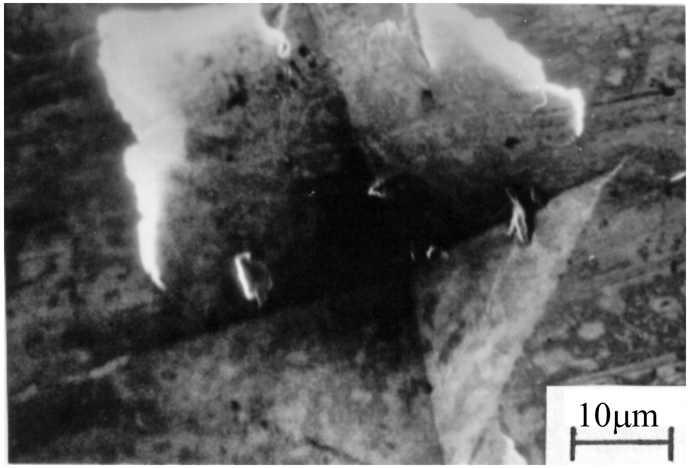
***A.Inoue* has shown that Al alloys with disperse strengthening by metastable intermetallic phases with a quasicrystalline structure can be produced by rapid solidification.**

Nanohardness of $Al_{63}Cu_{25}Fe_{12}$ quasicrystal





Extrusion from indentation print P=5N, *ambient temperature*



New direction in powder metallurgy:

producing powders by the technique of rapid crystallization of the melt with the formation of non-equilibrium metastable structures (the solidification rate to 10^6 °C/s)

Techniques of producing powders:

- manufacturing powders by atomizing the melt with high-pressure water or by gas atomization;
- manufacturing flakes and ribbons by spinning on a rapidly turning metallic wheel.

Techniques of powder consolidation:

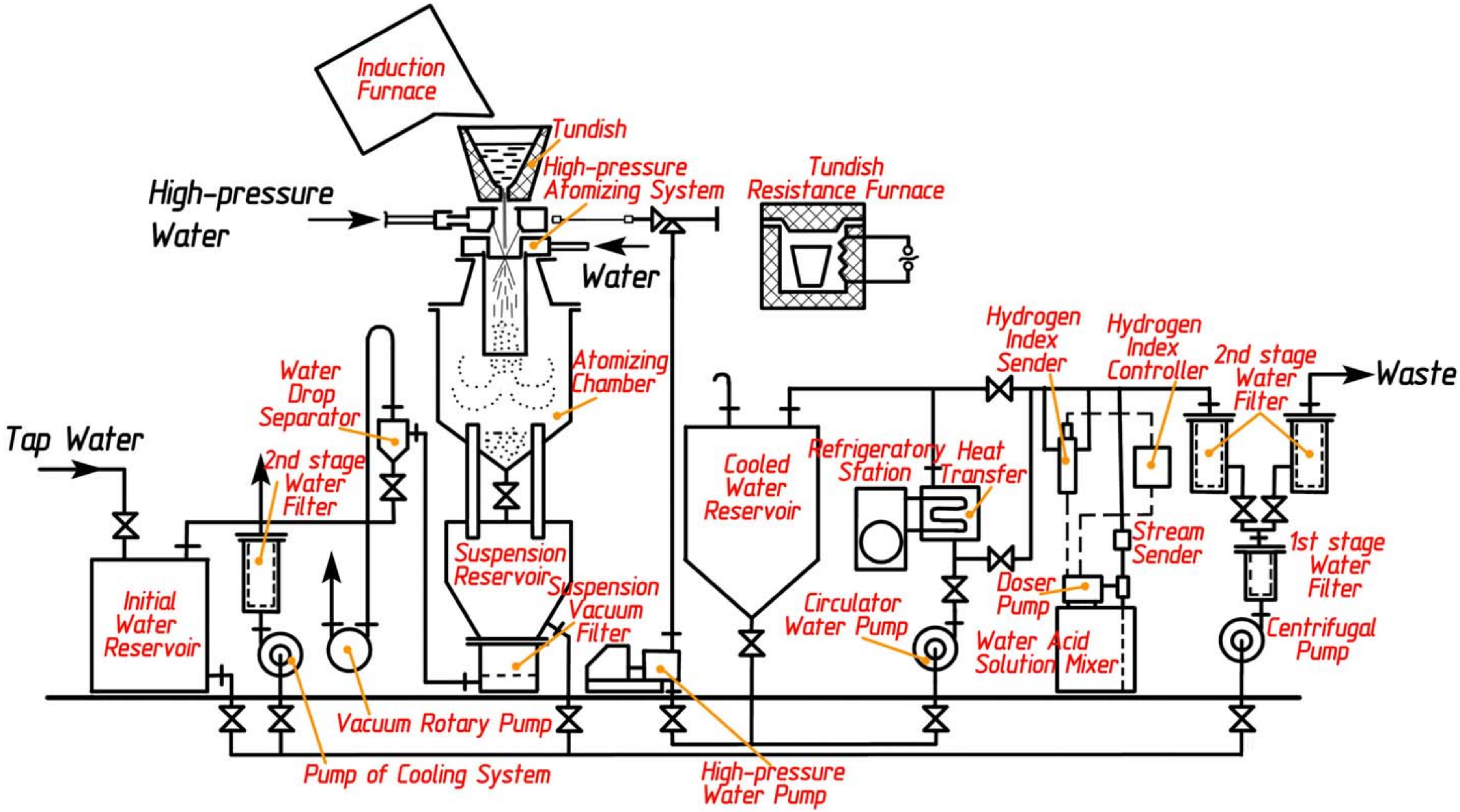
- isothermal pressing and extrusion of pressed billets in hermetic capsules;
- vacuum forging and extrusion of forged billets.

Powder consolidation is carried out by means of severe plastic deformation without sintering process

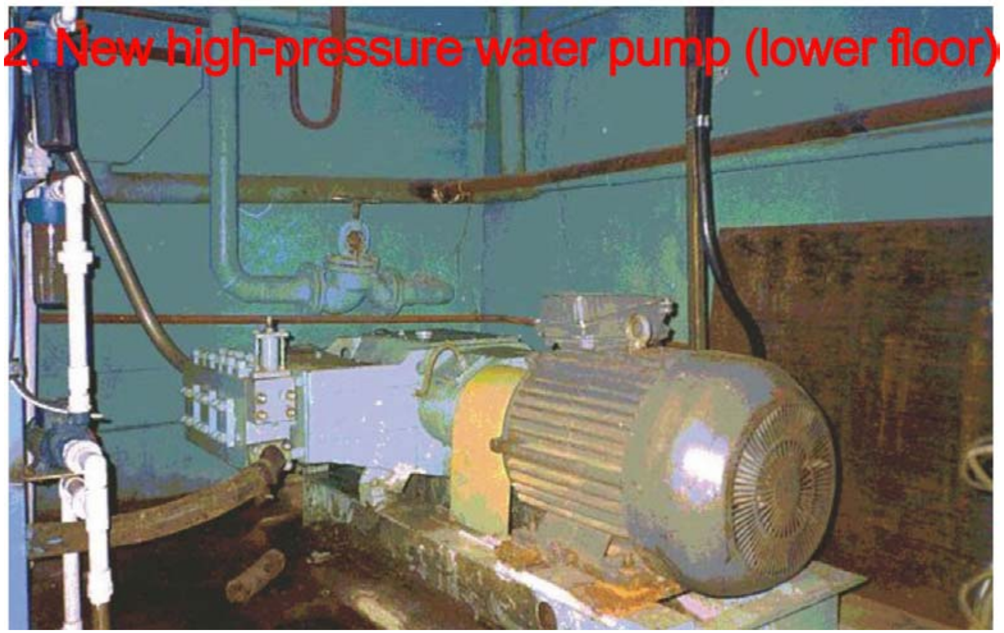
Advantages:

- a possibility of increasing the concentration of alloying elements, lowering the grain size, eliminating the liquation $\rightarrow$ improving mechanical properties;
- dissolution of harmful admixtures in the solid solution (e.g., *Fe* in *Al* that allows to use the recycled *Al* for producing high-strength *Al* alloys);
- creating new structural states: amorphous and quasicrystalline phases.

Schematic representation of the Al-alloys Water Atomization Unit



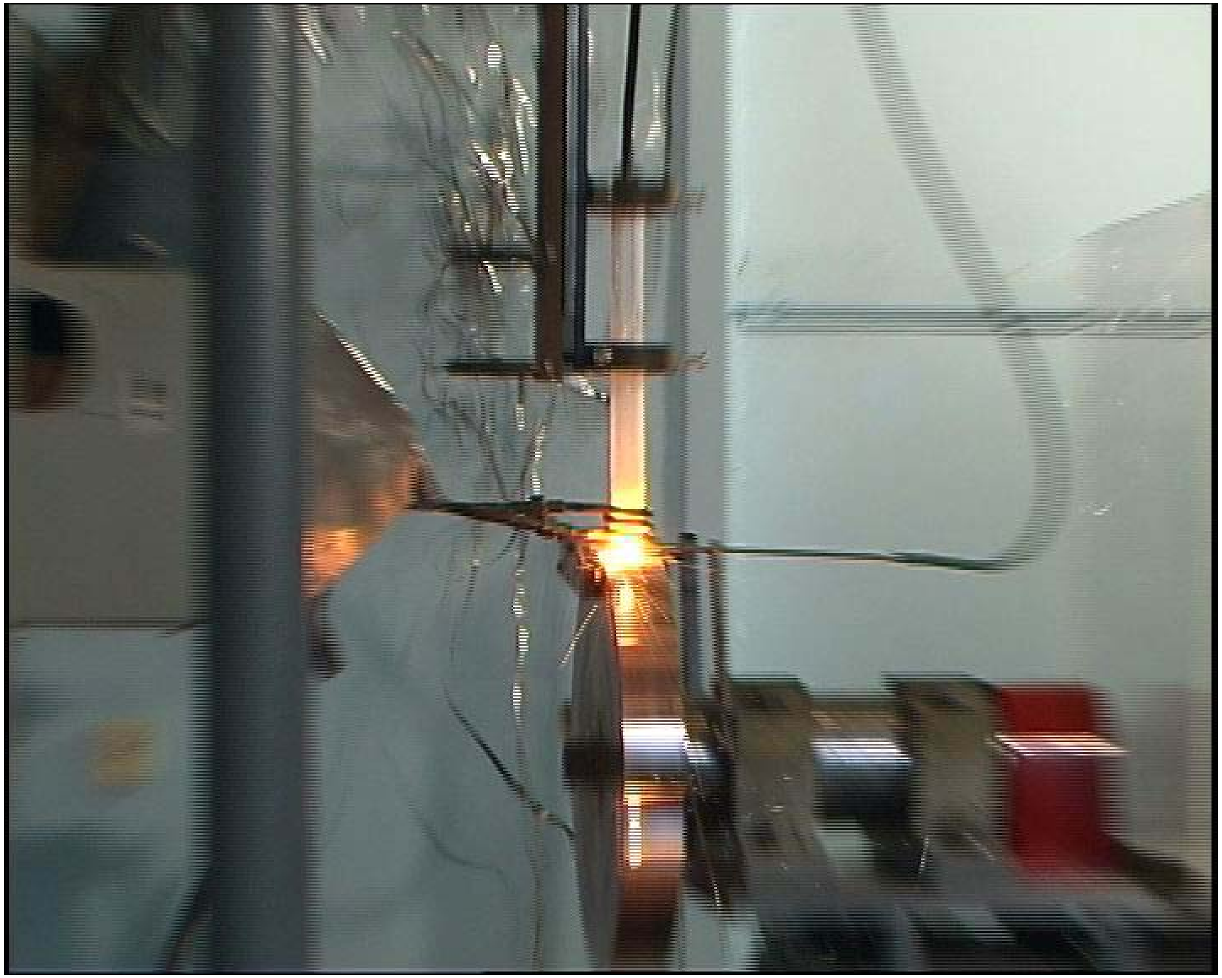
1. Atomization of melted Al alloys (upper floor)



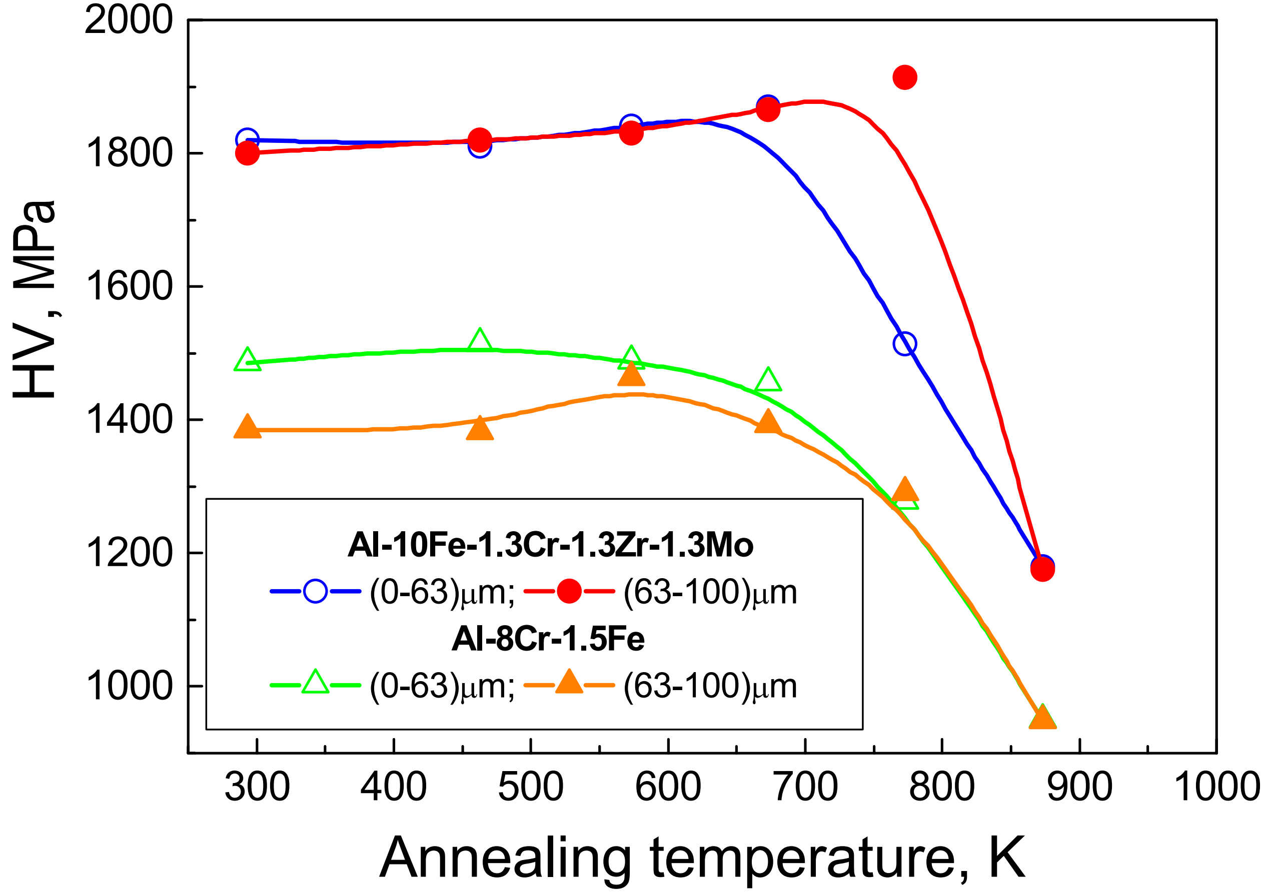
2. New high-pressure water pump (lower floor)

3. Hydrogen Index Controlled System and Cooled Water Reservoir

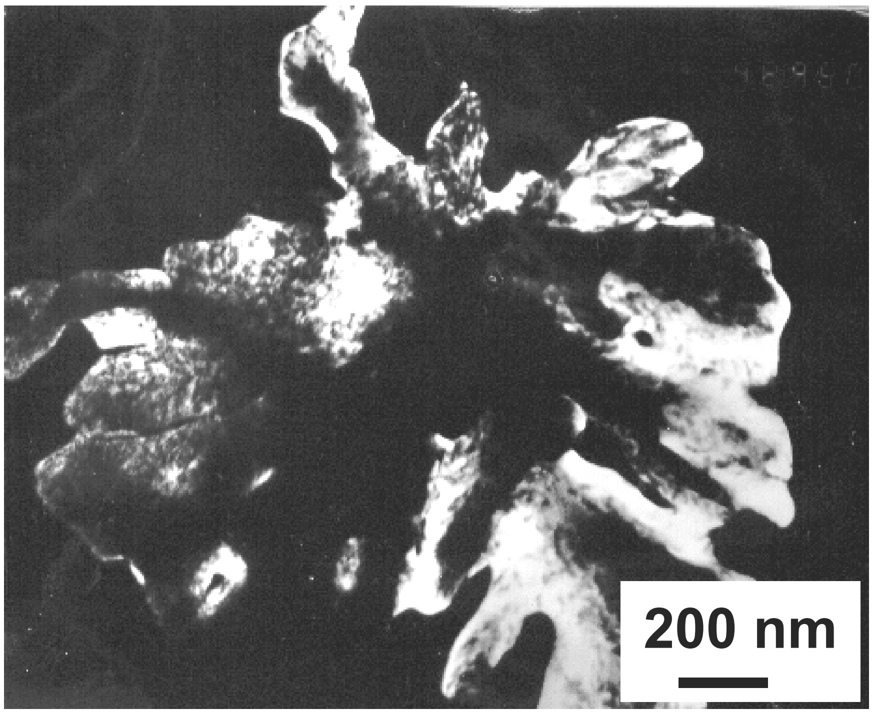
Production of melt-spun ribbons



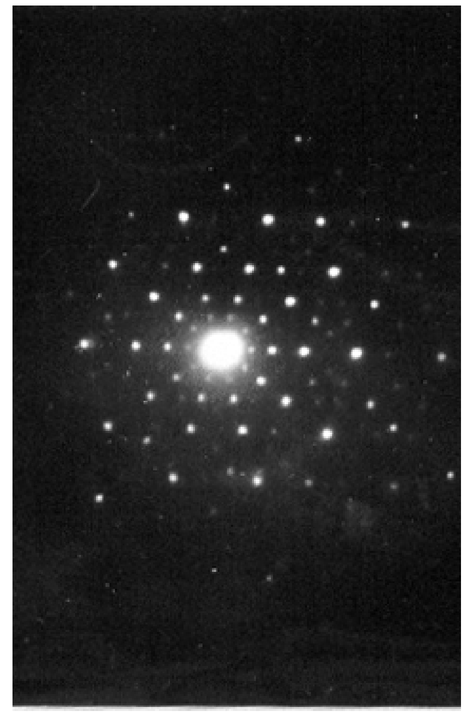
Change of hardness of PM extruded rods after isochronous annealing at various temperatures, holding time of 100 h



Structure, dark field image (a) and electron diffraction pattern of 5-fold symmetry (b) of an i-phase particle in ribbon $Al_{84.2}Fe_7Cr_{6.3}Ti_{2.5}$

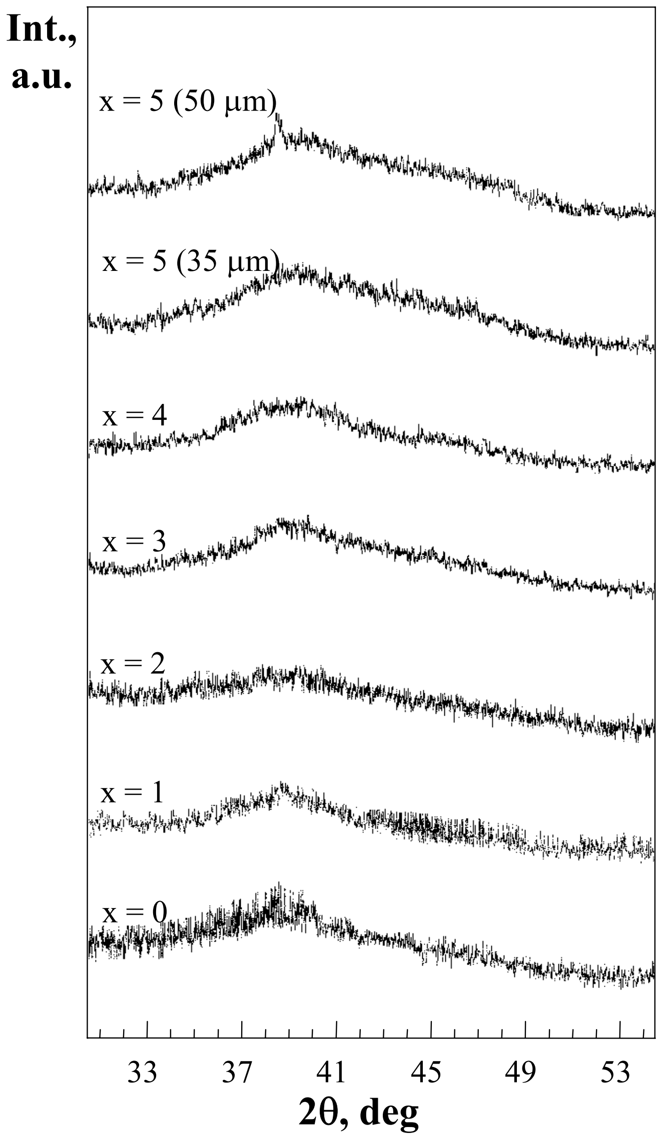


a

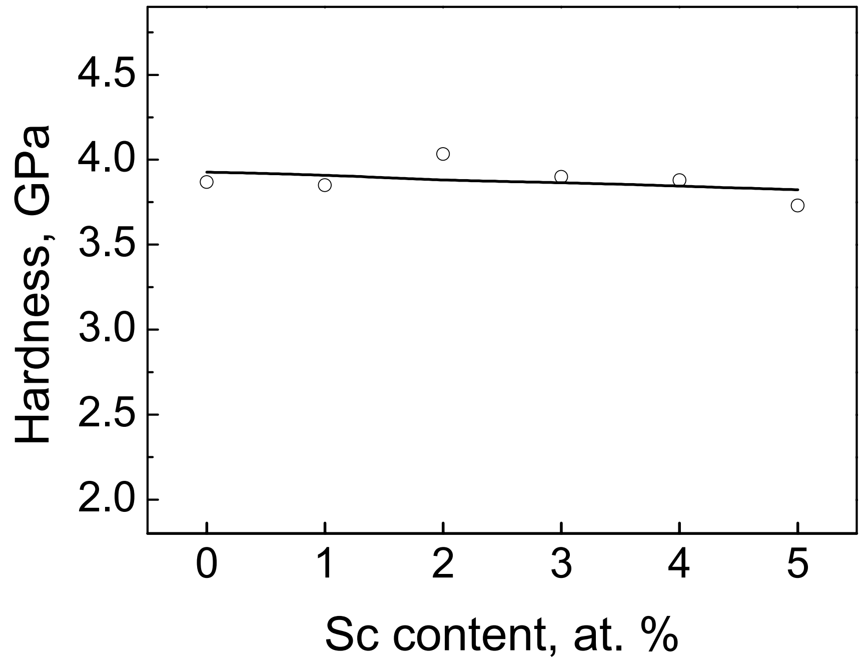


b

Alloys $Al_{85}Ni_{10}Ce_{5-x}Sc_x$

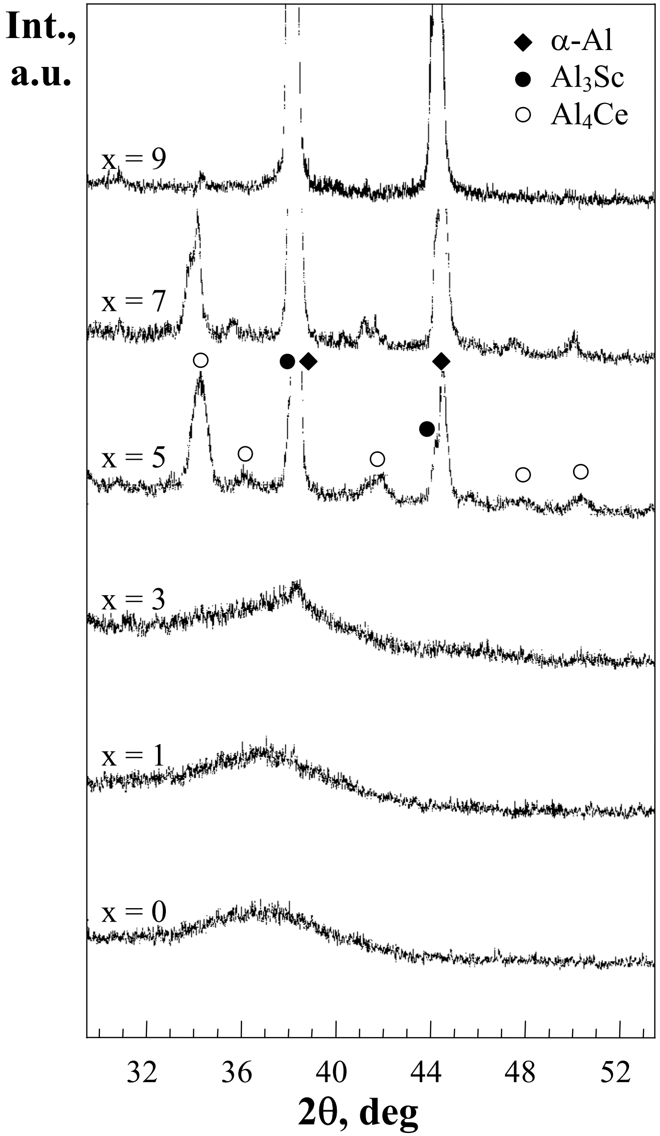


X-ray diffraction patterns of rapidly solidified $Al_{85}Ni_{10}Ce_{5-x}Sc_x$ alloys. The thickness of ribbons with x=0÷4 was of about 35 μm

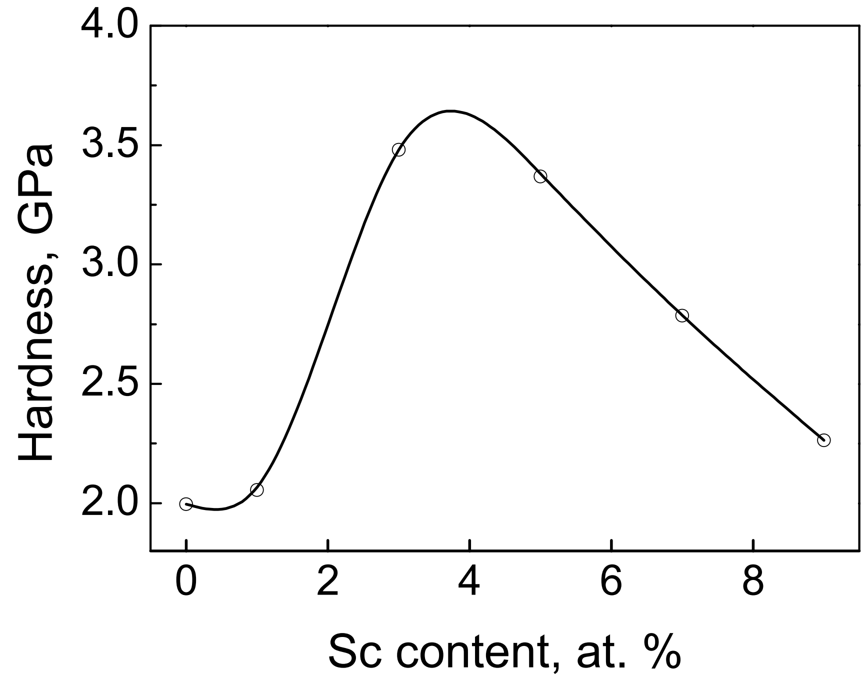


Hardness of melt-spun $Al_{85}Ni_{10}Ce_{5-x}Sc_x$ ribbons of about 35 μm in thickness

System Al - Ce - Sc



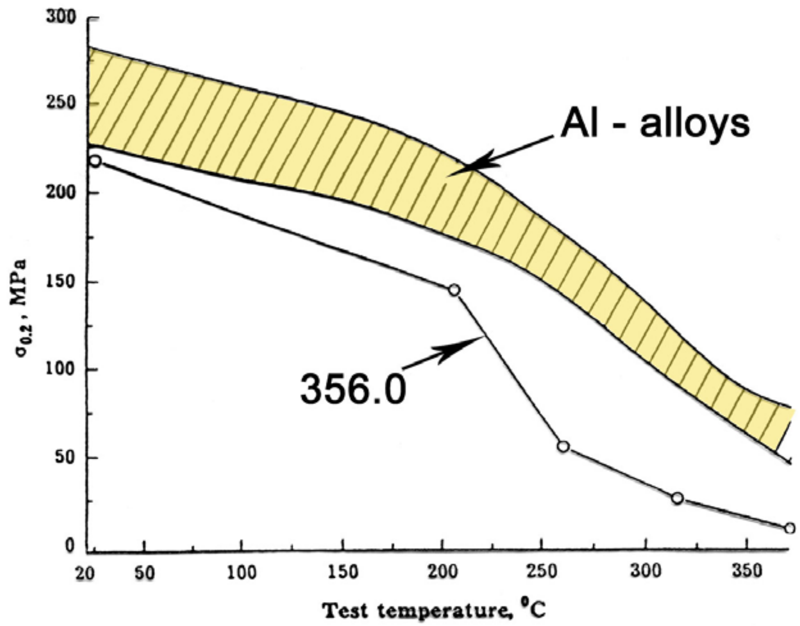
X-ray diffraction patterns of rapidly solidified $Al_{91}Ce_{9-x}Sc_x$ alloys



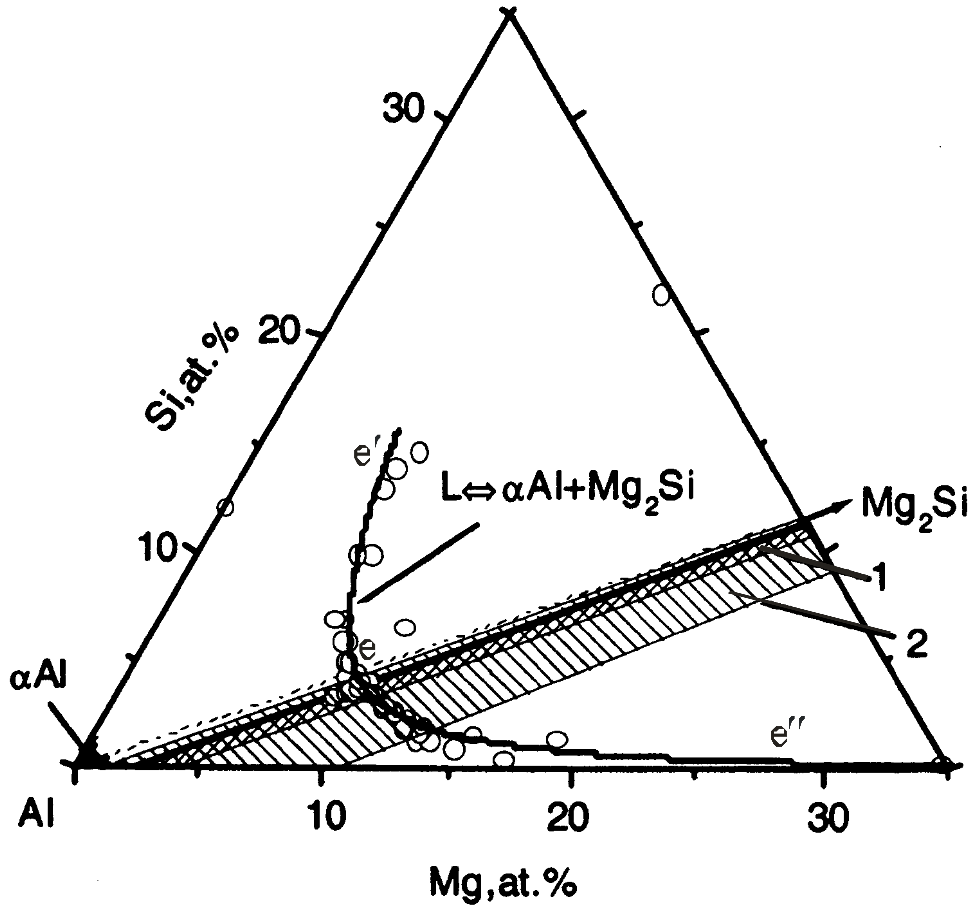
Hardness of rapidly solidified $Al_{91}Ce_{9-x}Sc_x$ alloys (P = 0.5 N)

New High-Temperature Scandium-Containing Cast Aluminum Alloys of Eutectic Type

Microstructure of the cast eutectic alloy



Temperature dependence of yield stress of the developed alloy (cross hatched region) and prototype alloy 356.0



Fragment of the phase diagram of the Al - Mg - Si system:

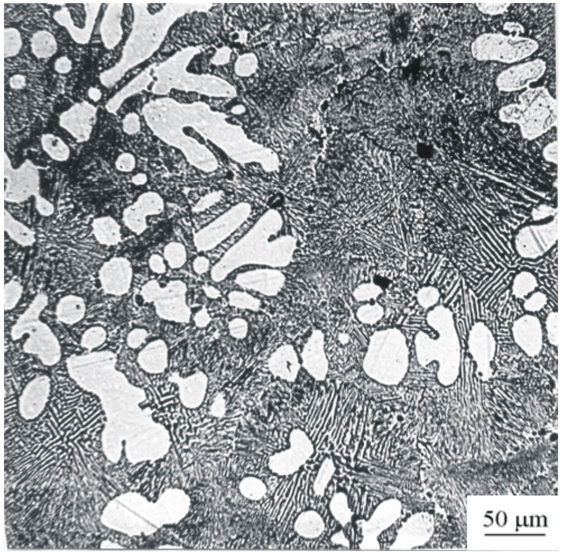
experimental line e'ee'' of the monovariant eutectic transformations $L \leftrightarrow \alpha$-Al + Mg_2Si (solid line). Thick straight line represents the quasi-binary section and dash line represents the stoichiometric section.

1 is the area of α-Al + Mg_2Si binary after annealing alloys,

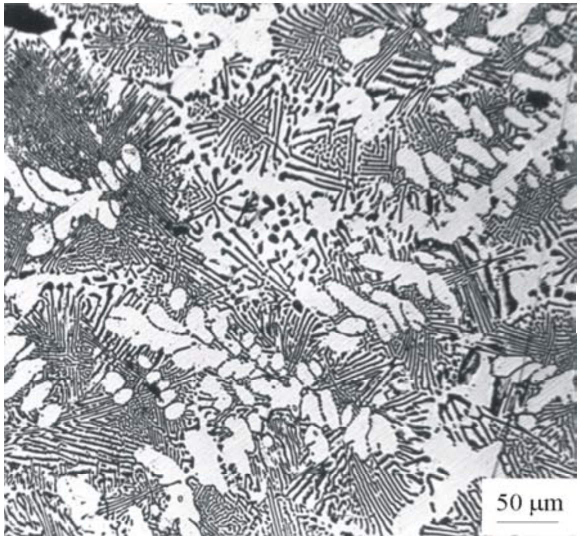
and 2 is the area of α-Al + Mg_2Si binary at crystallization alloys

The influence of Sc and Zr additions on the structure of eutectic Al – Si – Mg alloys

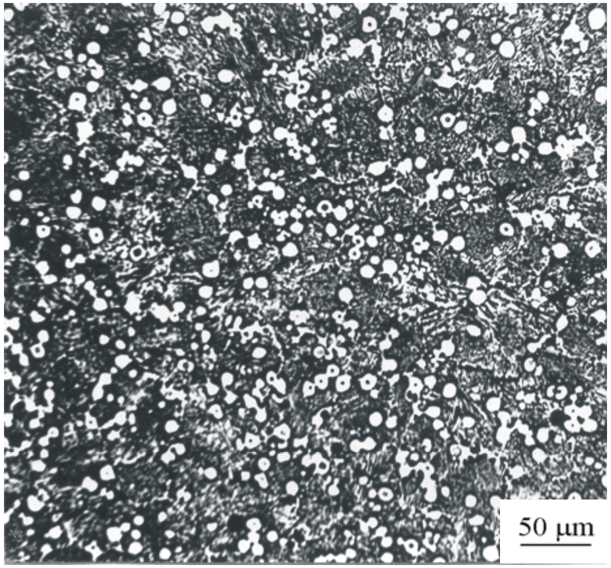
Al-Si-Mg



Al-Si-Mg + Sc



Al-Si-Mg + Sc, Zr



Mechanical properties of new cast eutectic aluminum alloys

Alloys for operation up to 150 ^{0}C

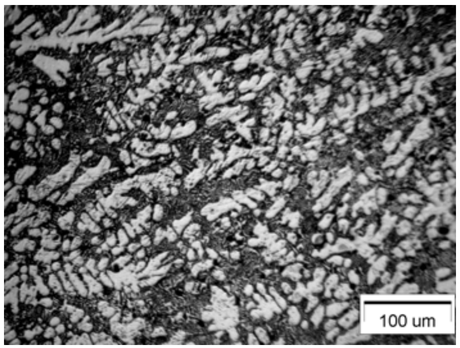
Alloy	Tensile properties			Hardness HV (MPa)	Heat treatment
	σ_{ys} (MPa)	UTS (MPa)	δ (%)		
Al - Mg – Si without alloying	210	320-370	3-5	971-1037	aging
Al - Mg - Si with complex alloying	300-430	370-530	0.5-1.5	1100-1500	quenching + aging
Al - Ge – Mg with complex alloying	490-620	540-660	1-2	1460-1860	quenching + aging

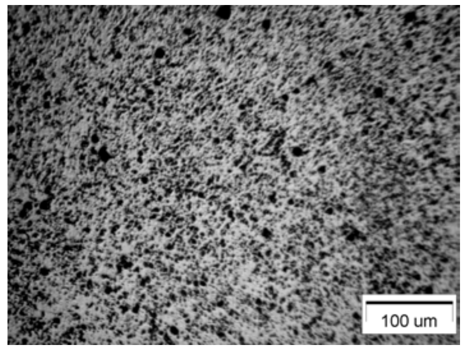
Alloys for high-temperature application

Alloy and Prototype	Tensile properties		Tensile properties			ΔT_c (^{0}C)	Heat treat-ment
	Time at temperature (h)	At indicated temperature (^{0}C)	σ_{ys} (MPa)	UTS (MPa)	δ (%)		
Al - Mg - Si (with complex alloying + dispersion particles Al_3Sc)							
ASM1	100	260	146-164	180-203	5-10	595-	aging
ASM2	100	315	91-115	102-130	13-15	599	
354.0	100	260	65	80	35	-	T61
	100	315	35	40	85		
356.0	10000	260	35	53	35	555-	T61
	10000	315	21	28	60	615	

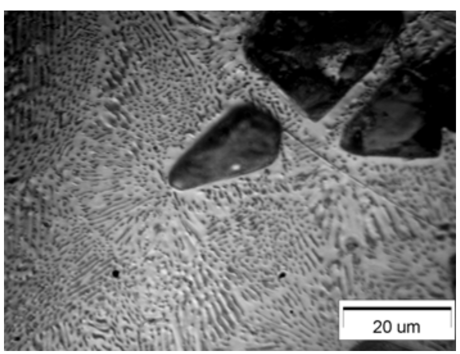
THE STRUCTURE AND MECHANICAL PROPERTIES OF CAST ALUMINUM ALLOYS BY FRICTION STIR PROCESS (FSP)

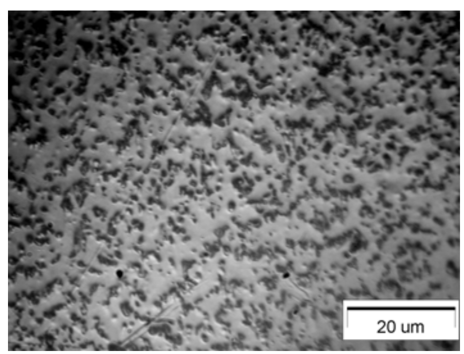
before FSP | **after FSP**



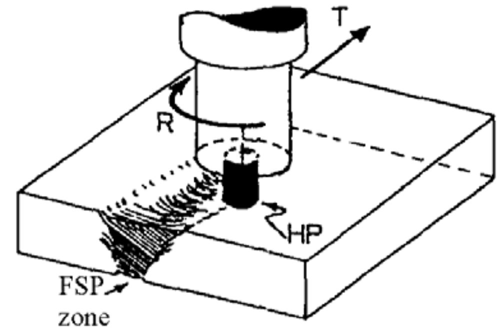


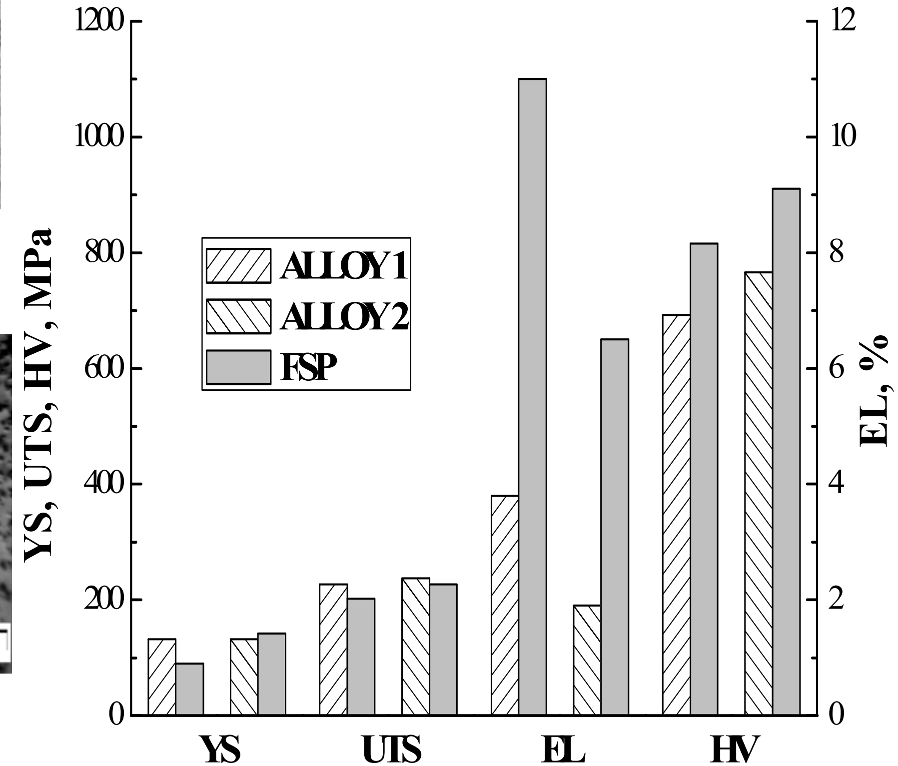
hypoeutectec alloy 1



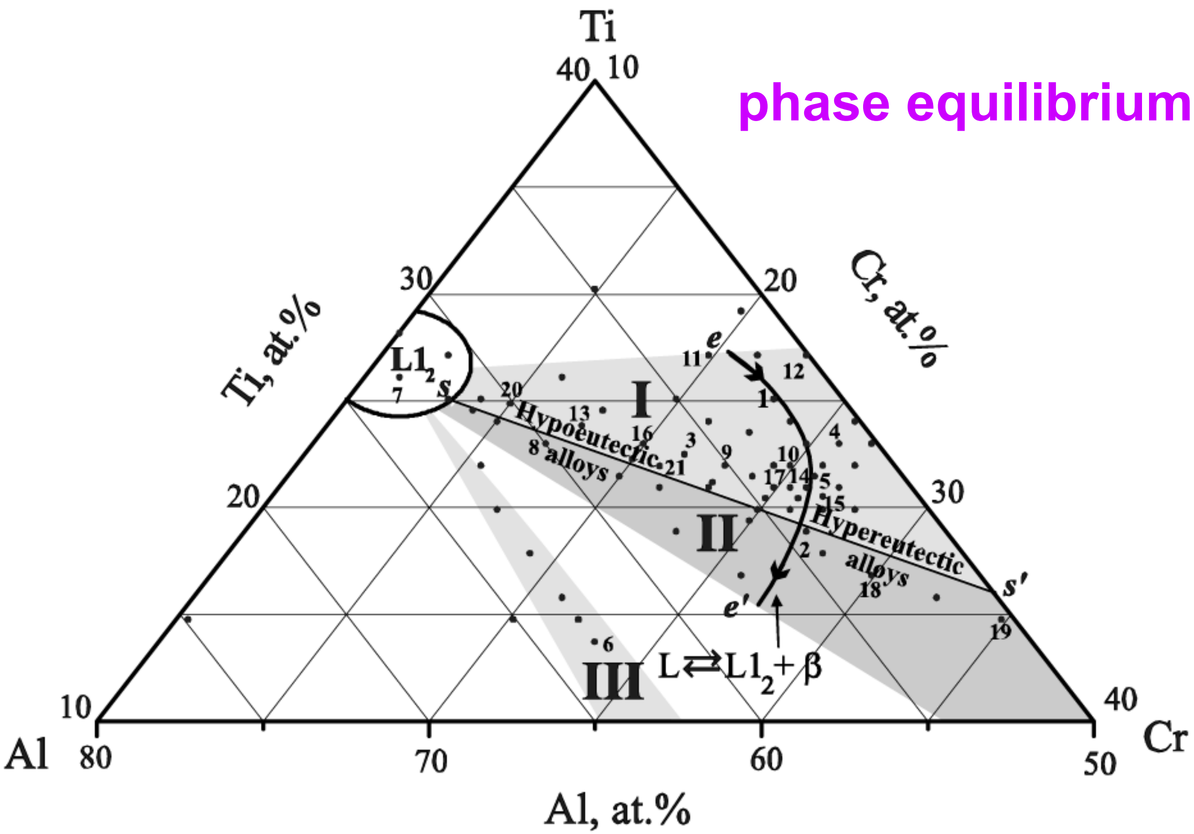


hypereutectic alloy 2





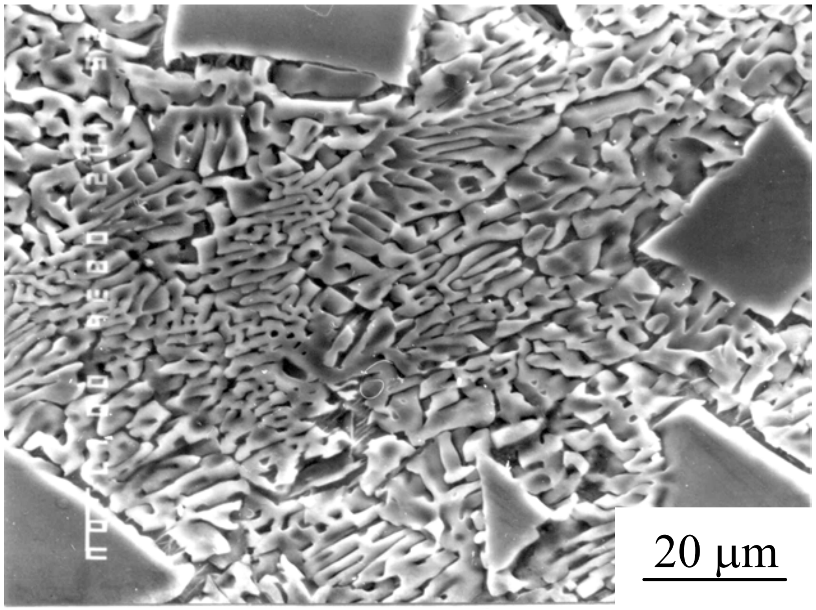
Development of elevated temperature eutectic cast alloys on the base of intermetallic phases



Portion of the liquidus surface at the Al-rich corner of phase diagram Al-Ti-Cr system

In the ternary Al - Ti - Cr system experimentally a large compositional region has been established, in which the eutectic transformation of a melt into two solid phases is realized: L ↔ L1$_2$ + β. This transformation is univariant and occurs in a narrow temperature interval from 1275 °C to 1250 °C, and the temperature interval of this transformation does not exceed 10 °C.

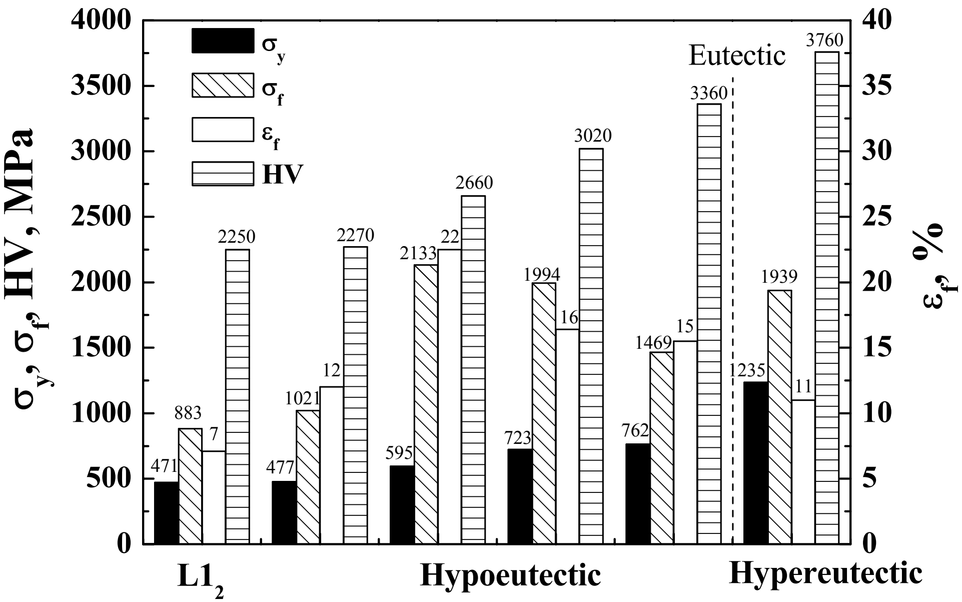
Development of elevated temperature eutectic cast alloys on the base of intermetallic phases



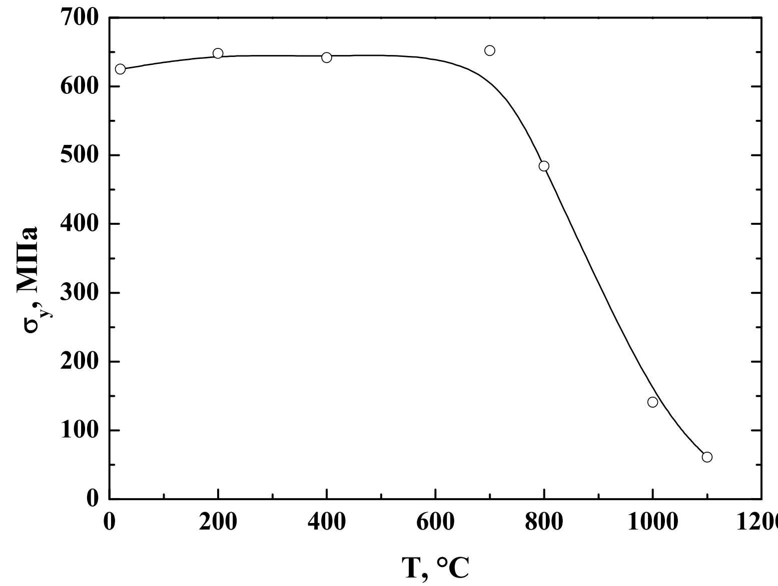
microstructure of hypoeutectic ($L1_2$+β) alloy

The periodic structure of eutectic ($L1_2$+β) alloys is formed by alternate lamellae and/or fibers of two phases: $L1_2$ and β. Primary dendrites of these phases have different forms: in hypoeutectic alloys, primary dendrites of the phase $L1_2$ are crystallized in the faceted form, but dendrites of the β-phase are unfaceted in hypereutectic alloys

Development of elevated temperature eutectic cast alloys on the base of intermetallic phases



Mechanical properties in compression tests and hardness of as-cast alloys



Temperature dependence of yield stress

Alloys containing two cubic phases $L1_2$ and β have high mechanical properties, exceeding that of single-phase $L1_2$ alloys: Young's modulus up to 190 GPa; hardness up to 3000 MPa in the temperature interval of 20-800 °C; compressive and bending strength up to 2000 MPa and 600 MPa, respectively;deformation before fracture ε^c up to 22%